What do we know about the influence of vacuum on bacterial biocenosis used in environmental biotechnologies?

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Abstract
The article aims to show the increased interest in the applications of vacuum in the area of environmental biotechnology and the lack of research related to the effects of vacuum on bacteria and microbial communities. Information on the impact of vacuum on bacteria is limited and often comes from unrelated research fields. In most cases (astrobiology research, food preservation technologies), the exposure of microorganisms in vacuum is permanent for the whole life of a cell. In environmental science applications, the exposure of microorganisms containing media such as sludge or soil in vacuum is rather persistent, and lower values of vacuum are used. Vacuum is used or proposed to be used in wastewater treatment, anaerobic digestion, sludge treatment, soil remediation and mining. Usually, vacuum is used to remove gases from the test medium, so a purely physical process is applied. However, most reports show the influence of vacuum on biological processes and its efficiency, as well as on the community structure.

Keywords
Vacuum · Pressure · Environmental biotechnology · Bacteria

Introduction
Pressure is an important parameter that can profoundly influence cell growth and proliferation. Life on Earth is supported by pressure conditions from 310 hPa (top of Mount Everest) through 1013 hPa at sea level to 1.1 x 10^6 hPa at the Mariana Trench, the oceans' deepest point. This is probably the reason why the effect of pressure on living systems and biomolecules has been intensively studied, mainly regarding pressures above the atmospheric value (atmospheric pressure) and much higher than the highest natural value (the food industry uses pressures up to 8 x 10^6 hPa). Air pressure decreases exponentially from the highest value above sea level, and most terrestrial life is supported in atmospheric pressure conditions close to values at sea level. Vacuum is represented by the pressure below Earth sea level. It is commonly used for degassing and transportation of matter. In the food industry, it is used for packing in order to preserve food products from spoiling and prolong their shelf life (e.g. Hernández-Macedo et al. 2011).

Research on the influence of vacuum on bacteria and yeasts is one of the most developed fields. Another much studied area is the astronomical science, and it focuses on the probability of life on Mars, where the atmospheric pressure on the surface ranges from 0.3 to 11.5 hPa (e.g. Frösler et al. 2017; Podolich et al. 2017). The number of publications in these two areas would allow for the creation of separate literature reviews.

Biotechnology is a field where the knowledge about features and abilities of microorganisms, mechanisms of bioprocesses and life's optimal conditions allow to create new or optimise current technologies to be used in order to serve humans. The existing data on the vacuum effect on biological processes and microbial cells allows to assume that the application of vacuum can be much more extended than currently, bringing new possibilities for the improvement of control strategies and the efficiencies of different processes.

Table 1 presents the results of searching publications containing in the title, abstract or keywords vacuum bacteria and selected words representing the mentioned research areas. Assuming that the appearance of the word vacuum and bacteria in the title, abstract or keywords is synonymous with conducting research on the effects of vacuum on bacteria in...
an adequate research area, it can be seen that vacuum is often used in environmental research; however, the number of publications on bacteria is small. Although this assumption is highly imperfect, it shows the lack of biological research on the impact of vacuum on bacteria. Environmental biotechnology is mainly based on the use of very diverse bacterial biocenosis, and the research is based on studies of the entire biocenosis, its abundance or biodiversity. In the case of biological research in the field of food technology or astrobiology, research is often carried out with the use of pure cultures or mixtures of a few species. In these cases, the word bacterium is not present but the name or names of the strains tested. The number of publications regarding the effect of vacuum on bacteria is therefore difficult to estimate; however, from the author’s subjective observations, it appears that the relationships between the areas discussed are similar to those shown schematically in Fig. 1.

In many examples presented in the next sections, the use of vacuum is not intended to treat microorganisms but to enforce certain physicochemical processes. In the meantime, however, microorganisms are exposed to vacuum. The most common applications of vacuum in environmental biotechnology are presented in Fig. 1. This short review aims to show the potential of vacuum and the gaps in our knowledge.

### Table 1

The number of publications containing in the title, abstract or keywords the word vacuum and other selected words (according to https://www2.scopus.com)

| Field of science          | Word in title or abstract or keywords | Word in title or abstract or keywords | Number of papers |
|---------------------------|---------------------------------------|---------------------------------------|------------------|
|                           | Without “bacteria” in title or abstract or keywords | With “bacteria” in title or abstract or keywords |                   |
| Food technology           | Vacuum                                | Food preservation                     | 824              |
|                           |                                       | Vacuum                                | 1727             |
|                           |                                       | Wound therapy                         | 4428             |
|                           |                                       | Wound treatment                        | 4034             |
| Medicine                  | Vacuum                                | Space                                 | 24217            |
|                           |                                       | Martian conditions                    | 124              |
|                           |                                       | Mars                                  | 561              |
| Astrobiology              | Vacuum                                | Space                                 | 126              |
|                           |                                       | Martian conditions                    | 14               |
|                           |                                       | Mars                                  | 25               |
| Biotechnology             | Vacuum                                | Biotechnology                         | 37               |
| Environmental biotechnology | Vacuum                              | Environmental biotechnology           | 24               |
|                           |                                       | Soil bioremediation                   | 52               |
|                           |                                       | Biological sludge                     | 84               |
|                           |                                       | Biomining                             | 1                |
|                           |                                       | Waste fermentation                    | 68               |
|                           |                                       | Sludge drying                         | 112              |
|                           |                                       | Sludge degassing                      | 14               |
|                           |                                       | Wastewater degassing                  | 10               |
|                           |                                       | Electricity production                | 173              |
|                           |                                       | Microbial fuel cell                   | 19               |

### Use of vacuum in environmental biotechnologies

The environmental technologies and the applications of vacuum where it may have the potential to influence exposed bacteria are presented in Table 2. In the aforementioned applications, the goal is to achieve specific desired physical or chemical effects, without deliberately affecting microorganisms. The obtained response of microorganisms is either not recognised or recognised as a consequence of physicochemical but not biological processes.

### Wastewater treatment

In wastewater and sludge treatment, vacuum is usually used for degassing of wastewater or sludge. The degassing process is based on Henry’s law, and in its very general form, it deals with the dependence of gas solubility on the pressure value. The degassing process removes gas bubbles from mixed liquor (activated sludge) and reduces the dissolved gases concentration. In the sludge that reaches the final sedimentation stage (atmospheric pressure), the dissolved nitrogen gas concentration is well below the saturation level. Thus, gas molecules produced in the sedimentation tank dissolve in the liquid.
instead of forming bubbles. Accumulated bubbles can result in sludge flotation what is undesirable. As a consequence of degassing, the activated sludge settles well at the settling stage without the formation of a layer of partially settled or floating solids (Maciejewski et al. 2010; Gnida and Witecy 2018). The separation of solids (activated sludge) from treated wastewater is one of the most crucial and problematic issues of a wastewater treatment plant (WWTP). The enhanced ability of activated sludge to settle and thicken at the final sedimentation stage allows WWTP operators to increase the sludge amount in the biological reactor (i.e. amount of bacteria involved in the process) and improve the removal of contaminants. The degassing of activated sludge occurs due to a short-term (30 sec) reduction of pressure to ca. 50 hPa. As the degassing unit is located between the reaction stage and the settling stage, activated sludge is treated by vacuum once in a time equal the hydraulic retention time. The system has been implemented in several places in Poland, Sweden, China, Estonia and Canada, and it presents a great improvement in regards to nutrients removal, especially denitrification (Maciejewski and Timpany 2008; Maciejewski et al. 2010; Maciejewski et al. 2013). Is the effect, however, simply the result of an increase of bacterial/sludge density in the reaction tank? In fact, only the settling properties of activated sludge and the overall WWTP control results have been presented so far (Maciejewski and Timpany 2008; Maciejewski et al. 2010; Maciejewski et al. 2013; Haghighatafshar et al. 2017). However, there is a suspicion that sudden vacuum conditions can be a stressful factor for bacteria and cause a change in their metabolic activity (Gnida 2015; Gnida 2018).

### Anaerobic digestion

In anaerobic treatment, vacuum could be useful in controlling the anaerobic digestion process. From an industrial point of view, the optimisation of hydrogen production is of the highest importance. In order to reach a high hydrogen production, the produced hydrogen has to be removed from a headspace as the accumulation of hydrogen causes inhibition of hydrogenesis (Rajhi et al. 2016). This is commonly achieved by stripping with an inert gas (e.g. N₂ gas). The idea of using vacuum for this purpose has been

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**Table 2** Use of vacuum in selected branches of environmental biotechnology

| Branch of technology | Aim of lowering pressure | Effect on process of microbials                     | Pressure, mbar | Exposure          | Source                           |
|----------------------|--------------------------|---------------------------------------------------|----------------|-------------------|----------------------------------|
| Wastewater treatment | Degassing                | Improvement of sludge settling                     | 50             | Intermittent, app. 30 sec | Maciejewski et al. 2010          |
|                      | Microbial fuel cells     | Higher production of electricity                   | 50–750         | Continuous        | Xiao et al. 2013                 |
|                      | Sludge disintegration    | Damage of bacterial cells                          | 20             | 5–30 min          | Abbasi 2003                      |
|                      | Degassing in anaerobic digester | Higher fermentation efficiency, change in community structure | not given | Continuous | Rajhi et al. 2016 |
|                      | Sludge drying            | Improvement of drying rates                         | 74–268         | Continuous        | Sagberg 2004; Yan et al. 2009    |
|                      | Soil remediation, suction of gases | Volatile compounds removal                        | not given      | Intermittent, unspecified | Thornton et al. 2007 |
| Soil treatment       | Bioleaching, intermittent liquid removal | Change in community structure                       | not given      | Intermittent, 90 sec, unspecified | Rzhepishevska et al. 2005 |
|                      | Biomining of peatland    | Change in community structure                       | not given      | Intermittent, unspecified | Croft et al. 2001                |
verified by several research teams, which obtained opposite results. Sonnleitner et al. (2012) argue that the application of pressure of 305 hPa allows nitrog en stripping to be omitted and hydrogen yield was close to the theoretical maximum. In contrast, continuous reactors vacuumed to 284 hPa by Kataoka et al. (1997) and 600 hPa by Clark et al. (2012) showed no or a non-significant effect on gas production, respectively. Meanwhile, other researchers found that vacuum-derived partial pressure may generate different hydrogen production yields depending on the value of hydraulic retention time. All vacuumed reactors, however, revealed a high hydrogen production efficiency with the desired product composition reached in acetate and butyrate (Lee et al. 2012). The effect of applying vacuum on dark fermentation systems was analysed by Rajhi et al. (2016). The dark fermentation is fermentative conversion of organic substances to biohydrogen in the absence of light. The application of vacuum promoted an increase in the diversity of hydrogen-producing bacteria (*Clostridium*), as well as favoured the dominance of acetoclastic over hydrogenotrophic methanogens. In addition, significantly more OTUs (operational taxonomic units) were found in the vacuum-exposed community. The application of vacuum (its value is not presented, but the used equipment suggests that it was not very low) caused a higher biogenic hydrogen and methane production, which is a very promising perspective. Unfortunately, there are no other data available regarding the influence of vacuumed headspace on a fermentative bacterial community. Both positive and contradictory results, however, testify to the research and development potential of the application of vacuum in anaerobic processes.

One of the ways to improve anaerobic sludge digestion and accelerate rate-limiting hydrolysis is sludge disintegration. There are plenty of methods of a mechanical, chemical or biological nature that are used for that purpose and are described by Zhen et al. (2017). Although this review is reliable, it does not include the technology based on the use of vacuum presented by Abbassi (2003). Sludge exposed to 20 hPa for 5–30 minutes was investigated. Vacuum was found to interrupt bacterial cells and cause the release of cell content, thus increasing the value of chemical oxygen demand in the supernatant. Such treatment enhanced hydrolysis of bacterial cells and improved sludge digestion. Another example of using vacuum to reduce waste and increase the energy recovery is to combine it with the steam treatment. This was found to promote the digestive efficiency of the sludge (Itoh et al. 2017).

The drying of sewage sludge has been found to be significantly more effective when assisted by vacuum (Sagberg 2004; Zhen et al. 2017). Vacuum conditions allow use of lower temperatures in the process (i.e. 50–90°C). Unless a lower temperature is used, the vacuum treatment decreased the number of *Escherichia coli* and spores of sulphite-reducing anaerobic bacteria (*Clostridia*) and f-specific bacteriophages in comparison to non-vacuumed samples (Sagberg 2004).

### Soil treatment

Vacuum is also used in the treatment of soil and groundwater environments for soil dewatering and reduction of pore water pressure, as well as the removal of volatile compounds from soil air. A vacuum heap biostimulation system was used for the treatment of excavated soil, which is recommended when the timeframe for its treatment is short. The improvement in the removal of polycyclic aromatic hydrocarbons (PAHs) after applying vacuum was significant, but no microbiological analysis was performed, and, therefore, there is no information regarding the vacuum extent (Eiermann and Bolliger 1995). Similarly, other researchers (Just and Stockwell 1993; Thornton et al. 2007) argue that the use of vacuum improves the efficiency of solvent-contaminated soil treatment and enhances further bioremediation. No microbiological research has been performed.

Intermittent vacuum conditions were used for the bioleaching of sulphidic tailings. Here, an extended community analysis was performed showing that a novel vacuum-based bioreactor provided conditions that were useful for bioleaching for selected bacterial populations. Setting aside numerous differences in configurations and chemical and physical conditions between a vacuum bioreactor and a reference (stirred) reactor, the molecular analysis of the bacterial community showed slight differences in the two assemblages (Rzhepishevska et al. 2005). It has not yet been assessed, however, whether the vacuum value and its duration influence the leaching efficiency and the bacterial activity. The mixture of solid matter (ore, tailings, etc.) and bacteria was exposed to alternating vacuum conditions where one cycle takes ca. 90 seconds and the vacuum condition comprises about 30% of the cycle. Thus, the bacteria are intermittently under a pressure stress that is not found in natural conditions. The authors do not provide information about the level of vacuum.

There are also examples of soil biotechnologies where microorganisms are exposed to vacuum. In soil bioremediation, vacuum is used to remove groundwater or soil vapour for further treatment in dedicated installations. The influence of such treatment on indigenous soil bacteria is rather limited, as most attention is focused on the efficiency of the removal of contaminants. Such treatment, however, can change the microclimate and humidity of the ground. Canadian researchers found that vacuum extraction in peatland while mined disturbs the bacterial population and the bacterial biomass carbon (Croft et al. 2001). Significantly fewer total bacteria were found in vacuum-treated land, especially of hemicellulolytic and cellulolytic properties. At the same time, there were more *Actinomycetes*.

### Microbial fuel cells

Very promising news comes from research concerned with microbial fuel cells. The introduction of vacuum into microbial fuel
cells caused only slight changes in the community structure, but the metabolic activity changed significantly. The attachment between extracellular polymeric substances and one of the electrodes was much stronger, resulting in the generation of power that was seven times higher as compared with the atmospheric environment (Xiao et al. 2013). Unfortunately, there is only one such report.

**Molecular biology analysis**

Apart from environmental biotechnology applications, there are some data about the influence of vacuum on bacterial cells. Hypobarophilic bacteria (Schuerger and Nicholson 2016) or yeasts (Gamage and Ohga 2017) were recovered from soils at high altitudes or from permafrost. The yeasts grew better in lower pressures of 850 hPa (Gamage and Ohga 2017) showing higher mycelial growth. Nicholson et al. (2010) found that the putative low-pressure barrier for the growth of Earth bacteria is ca. 25 hPa. The same authors argued that at the near-inhibitory low pressure of 50 hPa, *Bacillus subtilis* evolved an enhanced growth ability. A pressure downshift caused an up-regulation of some genes, and the regulation was different in response to the temperature versus the pressure downshift (Fajardo-Cavazos et al. 2012). The latest reports provide data that permafrost bacteria from the genera *Bacillus*, *Carnobacterium*, *Clostridium*, *Cryobacterium*, *Exiguobacterium*, *Paenibacillus*, *Rhodococcus*, *Serratia*, *Streptomyces* and *Trichococcus* may grow even at 7 hPa (Schuerger and Nicholson 2016).

Sarapirom et al. (2011) investigated changes in the topological form of extracellular plasmid DNA (deoxyribonucleic acid) due to lesions in DNA under vacuum conditions. The results show that vacuum can cause an increase in the relaxed form by about 50% as compared with that of the natural control and that this mainly occurs when the pressure rapidly changes. This result indicates that the DNA change is predominantly caused by the pressure change instead of the pressure itself, even though the pressure is very low.

Such information, originating from the astrobiological field, may hint at what happened on a molecular level with extracellular polymeric substances and one of the electrodes when exposed to constant or periodical vacuum. How does this affect the community structure and ecology?

**Conclusion**

Studies on the influence of pressure on microorganisms are quite extensive, while the influence of vacuum is a rather little recognised field. Here, only such applications of vacuum among environmental biotechnologies are presented where the bacteria involved in the technology are exposed to vacuum conditions. The few research reports on the impact of vacuum on biological processes come from various areas of environmental biotechnology. Most of the obtained results indicate that vacuum can also have biological, besides physicochemical, effects on microorganisms or communities. The results of molecular studies indicate that the effects obtained will depend not only on the value and duration of exposure but also on the degree of change in the value and the cyclicity of action. In my opinion, there is an open research field here, awaiting to be explored, which holds a lot of interest.

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**Compliance with ethical standard**

**Conflicts of interest** The authors declare that they have no conflict of interest.

**Research involving human participants and/or animals** This review does not include any researches with human participants or animals.

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**References**

Abbassi BE (2003) Improvement of anaerobic sludge digestion by disintegration of activated sludge using vacuum process. Water Qual Res 38:515–526. https://doi.org/10.2166/wqrj.2003.033

Clark IC, Zhang RH, Upadhyaya SK (2012) The effect of low pressure and mixing on biological hydrogen production via anaerobic fermentation. Int J Hydrogen Energy 37:11504–11513. https://doi.org/10.1016/j.ijhydene.2012.03.154

Croft M, Rochefort L, Beauchamp CJ (2001) Vacuum-extraction of peatlands disturbs bacterial population and microbial biomass carbon. Appl Soil Ecol 18:1–12. https://doi.org/10.1016/S0929-1393(01)00154-8

Eiermann DR, Bolliger R (1995) Vacuum heat bioremediation of a PAH-contaminated gasworks site. In: Van Den Brink WJ, Bosman R, Arendt F (eds) Contaminated Soil. Soil & Environment, vol. 5. Springer, Dordrecht, pp 1189–1190

Fajardo-Cavazos P, Waters SM, Schuerger AC, George S, Marois JJ, Nicholson WL (2012) Evolution of Bacillus subtilis to enhanced growth at low pressure: up-regulated transcription of des-desKR, encoding the fatty acid desaturase system. Astrobiology 12:258–270. https://doi.org/10.1089/ast.2011.0728

Frösler J, Panitz C, Wingender J, Flemming H-C, Retterberg P (2017) Survival of Deinococcus geothermalis in biofilms under desiccation
and simulated space and martian conditions. Astrobiology 17:431–447. https://doi.org/10.1089/ast.2015.1431

Gamage S, Ohga S (2017) Effects of hypobaric and hyperbaric pressures on mycelial growth of isolated strain of wild Ophiocordyceps sinensis. Adv Microbiol 7:575–587. https://doi.org/10.4236/am.2017.77045

Gnida A (2015) Preliminary studies on the influence of negative pressure on activated sludge. In: Proceedings of International IWA Conference Nutrient Removal and Recovery. Gdańsk, pp 30

Gnida A (2018) Influence of negative pressure on activity of activated sludge bacteria. In: Proceedings of International Conference Biotechnology - Research and Industrial Applications. Wrocław, pp 36

Gnida A, Witcycz D (2018) Preliminary studies on the influence of negative pressure on activated sludge flocs. Quarterly of Environmental Engineering Design 170:51–60. https://doi.org/10.5604/01.3001.0012.7462

Haghighatashfar S, Wilen BM, Thunberg A, Hagman M, Nyberg A, Grundestam J, Mases M, la Cour J (2017) Laboratory-scale assessment of vacuum-degassed activated sludge for improved settling properties. Environ Technol 38:2193–2201. https://doi.org/10.1080/09593330.2016.1251498

Hernández-Macedo ML, Barancelli GV, Contreras-Castillo CJ (2011) Microbial deterioration of vacuum-packaged chilled beef cuts and techniques for microbiota detection and characterization: a review. Braz J Microbiol 42:1–11. https://doi.org/10.1590/S1517-8382201100010000I

Itoh K, Yamamoto T, Maeda K, Tachikawa H (2017) Consecutive vacuum degassing and steam treatment of sewage sludge using a steam ejector. KAGAKU KOGAKU RONBUN 43:57–62. https://doi.org/10.1252/kakoronbunshu.43.57

Just SR, Stockwell K (1993) Comparison of the effectiveness of emerging in situ technologies and traditional ex situ treatment of solvent-contaminated soils. In: Tedder W, Pohland F (ed) Emerging Technologies in Hazardous Waste Management III. ACS Publications, Washington, pp 238–277

Kataoka N, Miya A, Kiriyama K (1997) Studies on hydrogen production by continuous culture system of hydrogen-producing anaerobic bacteria. Water Sci Technol 36:41–47. https://doi.org/10.1016/S0273-1223(97)00505-2

Lee KS, Tseng TS, Liu YW, Hsiao YD (2012) Enhancing the performance of dark fermentative hydrogen production using a reduced pressure fermentation strategy. Int J Hydrogen Energy 37:15556–15562. https://doi.org/10.1016/j.ijhydene.2012.04.039

Maciejewski M, Timpany P (2008) New European BNR technology of mixed liquor vacuum degassing debuts for the Beijing 2008 Olympics. In: Proceedings of BC Water and Waste assoc. Annual Conference, Whistler

Maciejewski M, Oleszkiewicz JA, Golcz A, Nazar A (2010) Degasification of mixed liquor improves settling and biological nutrient removal. Water Pract Technol 5:1–7. https://doi.org/10.2166/wpt.2010.009

Maciejewski M, Oleszkiewicz J, Drapiaewski J, Golcz A, Nazar A (2013) Mixed liquor vacuum degassing (MLVD) – a highly effective and efficient method of activated sludge bulking and flush-out prevention in the wastewater treatment, with simultaneous improvement of total nitrogen removal. In: Proceedings of 7th European Waste Water Management Conference, Manchester

Nicholson WL, Fajardo-Cavazos P, Fedenko J, Ortiz-Lugo JL, Rivas-Castillo A, Waters SM, Schuerger AC (2010) Exploring the low-pressure growth limit: evolution of Bacillus subtilis in the laboratory to enhanced growth at 5 kilopascals. Appl Environ Microbiol 76:7559–7565. https://doi.org/10.1128/AEM.01126-10

Podolich O, Zaets I, Kukharenko O, Orlovskia I, Reva O, Khirunenko L, Nosnin M, Haidak A, Shpylova S, Rabbew E, Skoryk M, Kremenskoy M, Demets R, Kozyrovska I, De Vera J-P (2017) Kombucha multimicrobial community under simulated spaceflight and martian conditions. Astrobiology 17:459–469. https://doi.org/10.1089/ast.2016.1480

Rajhi H, Puyol D, Martinez MC, Díaz EE, Sanz JL (2016) Vacuum promotes metabolic shifts and increases biogenic hydrogen production in dark fermentation systems. Front Environ Sci Eng 10:513–521. https://doi.org/10.1007/s11783-015-0777-y

Rzhepishvskva OI, Lindström EB, Tuovinen OH, Dopsen M (2005) Bioleaching of sulfidic tailing samples with a novel, vacuum-positive pressure driven bioreactor. Biotechnol Bioeng 92:559–567. https://doi.org/10.1002/bit.20609

Sagberg P (2004) Hygienization of municipal sludge in automatically operated chamber filter presses with thermal vacuum drying. Water Sci Technol 50:53–60

Sarapirion S, Thongkumkoon P, Anunthabheboon S, Yu LD (2011) Vacuum effect on DNA lesion and genetic mutation of cells. Vacuum 86:374–379. https://doi.org/10.1016/j.vacuum.2011.08.00I

Schuerger AC, Nicholson WL (2016) Twenty species of hypobarophilic bacteria recovered from diverse soils exhibit growth under simulated martian conditions at 0.7 kPa. Astrobiology 16:964–976. https://doi.org/10.1089/ast.2016.1587

Sonntleiter A, Peintner C, Wukovits W, Friedl A, Schnizelhofer W (2012) Process investigations of extreme thermophilic fermentations for hydrogen production: effect of bubble induction and reduced pressure. Bioreact Technol 118:170–176. https://doi.org/10.1016/j.biotec.2012.05.046

Thornton EC, Gilmore TJ, Olsen KB, Giblin JT, Phelan JM (2007) Treatment of a chromate-contaminated soil site by in situ gaseous reduction. Ground Water Monit Rem 27:56–64. https://doi.org/10.1111/j.1114.1749.2006.00123.x

Xiao Y, Wu S, Zhang F, Wu YC, Yang ZH, Zhao F (2013) Promoting electrogenic ability of microbes with negative pressure. J Power Sources 229:79–83. https://doi.org/10.1016/j.jpowsour.2012.11.139

Yan J-H, Deng W-Y, Li X-D, Wang F, Chi Y, Lu S-Y, Cen K-F (2009) Vacuum and simulated space and martian conditions. Astrobiology 17:459–469. https://doi.org/10.1089/ast.2016.1480

Zhen G, Lu X, Kato H, Zhao Y, Li YY (2017) Overview of pretreatment of mixed liquor vacuum degassing technique for biogas production from municipal sludge. J Power Sources 347.https://doi.org/10.1016/j.jpowsour.2017.03.18

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