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Bio-solution for global sand crisis and sustainable organic agriculture in desert states

D. Štyriaková
ekolive s.r.o., Košice, Slovakia
Slovenian National Building and Civil Engineering Institute, Ljubljana, Slovenia

I. Štyriaková & J. Šuba
ekolive s.r.o., Košice, Slovakia

Felix Föhre
FB Flüssigboden GmbH, Leipzig, Germany

ABSTRACT: Sand is an important component of many everyday items, and currently sand is the second most extracted resource on earth after water, but it is not sustainable: we are running out of sand! The black market is booming, and the sand mafia is mining sand at any price. Desert sand is unusable, even Dubai must import it. The smooth surface and iron impurities prevent its industrial use. In this study, bacteria in the bioleaching test attacked the surface of the mineral grains and dissolved impurities including iron through organic acids. Furthermore, the liquid residue containing dissolved iron, organic acids and bacteria stimulated the growth plant what can be a valuable biofertilizer and biostimulant for organic agriculture. Desert states have fertility problems. Despite this, Qatar, for example, is aiming for self-sufficiency in vegetables "in five years". Results showed that bioleaching combined with magnetic separation resulted in iron removal of 73.23%. The sand after treatment can be suitable to produce clear flat glass, coloured container glass, insulating glass fibres or ceramics. The integrated technology based ecological study revealed overall as utilization potential of the desert sand and the liquid residue could support glass and food production in desert states.

1 INTRODUCTION

Sand is one of the main components of the modern glass, foundry, refractory, ceramic and construction industries. In recent years, there has been a sharp increase in demand for high-purity quartz for semiconductor chips, solar batteries, photovoltaic and flat panel displays, which are classified as advanced technology products. Quartz is one of the most important raw materials used in many industries. There are four types of sand: river sand, sea sand, desert sand and machine-made sand. Desert sand, as the name suggests, is sand from the desert.

1.1 *Industrial sand*

Sand is the main ingredient in the entire glass industry. The purity of the sand determines the colour, clarity, strength and other physical advantages of the glass products. The main glass

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products that use sand include colourless and coloured containers such as bottles and glasses, flat glass for windows and automobiles, glass fibre, glass fibre reinforcement, light bulbs, fluorescent tubes, televisions and computer screens. Its special applications include products such as piezoelectric crystals, optical products and glassy silica.

The Asia Pacific region accounts for 47% of global sand needs. Mitsubishi's Cape Flattery in Queensland is currently the largest high-grade silica operation in Australia, delivering ~2.5 million tons per year to Asian countries. In recent years, several regions in which sand is produced have been restricted for environmental reasons. In the past, sand was extracted from environmentally sensitive coastal, river or delta regions such as the Mekong Delta in Vietnam or the Yangtze River in China. Based on estimated world production the United States was the world's leading producer and consumer in 2018 and 2019 of industrial sand and gravel (Table 1). It is difficult to collect definitive data on silica sand and gravel production in most nations because of the wide range of terminology and specifications found among different countries. The United States remained a major exporter of silica sand and gravel, shipping it to almost every region of the world. The high level of exports was attributed to the high quality and advanced processing techniques used in the United States for many grades of silica sand and gravel, meeting virtually every specification. Estimated global demand for in 2020 sand by region is showed in Table 2.

Table 1. World mine production of industrial sand and gravel (USGS).

State		% of Global demand
United States	2018 (kt) 121,000	2019 (kt) 110,000
Australia	3,000	3,000
Bulgaria	7,250	7,300
Canada	2,500	2,500
France	9,310	9,300
Germany	7,500	7,500
India	11,900	12,000
Indonesia	5,540	5,500
Japan	2,520	2,500
Korea	4,300	4,500
Malaysia	10,000	10,000
Mexico	2,360	2,400
Netherlands	54,000	54,000
New Zealand	2,320	2,300
Poland	5,120	5,000
South Africa	2,400	2,400
Spain	35,500	36,000
Turkey	13,500	14,000
United Kingdom	4,000	4,000
Other countries	17,200	21,300

Table 2. Estimated demand for sand by region (source: Freedonia group).

Region	% of Global demand
Asia pacific	47%
North America	20%
Western Europe	16%
Eastern Europe	8%
Africa/Middle East	5%
Central and South America	4%

The Arabian Desert is the second largest desert in the world. The only two different types of construction sand available in Arabian Desert are fluvial sand (for concrete work) and aeolian dune (for mortar work). The scarcity of sand necessitates quality management of these deposits to ensure its availability for as long a period as possible. In addition, the desert states restrict the use of imported sand in all construction works. The desert sand is mainly composed of more than 95% quartz and long-lived minerals such as zircon, tourmaline, rutile and small amounts of feldspar and muscovite. With rapid industrial development, the demand for sand resources is increasing rapidly, but at the same time, sand resources on Earth are limited.

The petrography and heavy mineral content of various dune sands have been described in detail in an article by authors Pastore et al. (2021) with the following composition: Quartz, feldspar, plagioclase, lithic grains (volcanic, carbonate, other sedimentary and metasedimentary) and transparent heavy minerals, including: Zircon + Tourmaline + Rutile, Apatite, Titanite, Epidote, Prehnite + Pumpellyite, Garnet, Staurolite, Kyanite, Amphibole, Pyroxene, Olivine and others (Anatase, Sillimanite, Andalusite, Monazite, Topaz, Brookite). The chemical composition of the raw quartz sands (especially the content of SiO_2, Fe_2O_3 and Al_2O_3) is most important for their use and physical properties. The sand in the desert is formed by weathering and accumulation, and the pollutants cannot be removed as in river or sea sand, resulting in a high pollutant content in the sand, which is very slippery and does not meet the standards and limits for industrial use. To increase the purity of quartz and reduce the content of impurities to the desired levels, various physical and chemical processes are used industrially (Tuncuk & Akcil 2014).

As there will be around 9.3 billion people on earth in 2050 (Sahara Forest Project, 2012), the problem of providing sufficient food for these people will be enormous. Therefore, we need to think critically about new strategies to expand our ability to produce food in the future. Food production remains a challenge, especially for desert countries. Many Gulf countries have learned from the 2008/2009 food crisis that they cannot import food simply because they have the financial capacity to do so. Therefore, it is crucial to find new ways to produce as much food as possible locally to minimise the burden of food imports (Mbaga 2013).

1.2 *Quality improvement of silica sand and increasing of soil fertility*

The purification of silica sand is extremely important for many industries. Several techniques are available for the treatment of silica sand through the partial removal of iron, e.g., flotation, heavy separation, or magnetic separation. Other available techniques are based on the use of sulphuric acid, hydrochloric acid and phosphoric acid as demonstrated by (Tuncuk & Akcil 2014, Suratman & Handayani 2014, Zhang et al. 2012). These methods are very efficient in removing metal contaminants, but they are generally expensive and have significant environmental impacts.

Biological methods are also effective for the surface chemistry of clay minerals and the release of iron minerals from quartz particles (Štyriaková et al. 2012), and these methods have gained interest in recent years. Organic acids dissolve iron oxides by direct attack of H+ ions on the mineral matrix and keep them in solution by forming soluble complexes and chelates. Organic acids can be produced by fermentation using heterotrophic bacteria and serve as leaching agents for dissolving the iron oxides. This biotechnological route, using microorganisms to remove metal contaminants, could prove to be more cost-effective and environmentally friendly, resulting in effluents that are not harmful to nature and can be easily purified.

This process refers to the removal of unwanted mineral components from a silica sand through interaction with a microorganism that causes their selective dissolution (removal), thereby improving their quality and the possibilities of their industrial utilisation. Previous laboratory studies have shown that bacteria and fungi can be effectively used to remove iron from silica sand, kaolin, bauxite, and silica sand (Štyriaková et al. 2015, Šuba & Štyriaková 2015).

Consumers are increasingly concerned about food safety, rising residues in food and environmental issues as they become more concerned about their health. This is driving the need for organic inputs such as biofertilizers and biostimulants to improve soil fertility and crop yields. The use of chemical fertilisers and pesticides causes numerous environmental and health problems. Loss of soil structure and fertility is one of the main causes of soil degradation. Safe and environmentally friendly technologies could help in the sustainable restoration of degraded soils and fertilisation of crops and plants. Innovative, safe, and environmentally friendly technologies could help in the sustainable restoration of degraded soils. Bacteria with dissolved nutrients from natural minerals such as silica sand can restore the fertility of degraded soils. These microorganisms increase the bioavailability of nutrients by fixing nitrogen and mobilising key nutrients (phosphorus, potassium, and iron) in crops, and optimise soil structure by improving its aggregation and stability. Organic acids, produced naturally by bacteria, support growth, and yield and protect plants from diseases.

The aim of the present study was to investigate the removal of impurities, especially iron oxides, from silica sand using biological and physical methods to obtain a product of higher quality and purity. This product can be used in the glass industry and at the same time a biofertiliser is produced that can be used to improve soil fertility and help solve the problem of high food imports in desert countries.

2 MATERIALS AND METHODS

2.1 *Desert sand*

The desert sand used for the bioleaching experiment was obtained from the sand dunes of the Arabian Desert. Table 3 shows the chemical properties of this desert sand. The chemical analyses were carried out using a portable Vanta X-ray fluorescence spectrometer (XRF), which allows rapid and accurate elemental analyses of solid and liquid phases in laboratory quality.

Table 3. The chemical composition of desert sand.

SAND	Al	Si	S	Ti	Fe	Mn	Ca	Cu	Zn
(mg/kg)	7791	204,318	4403	469	2640	61	98,493	13	6

2.2 *Bioleaching*

Biological removal of iron from desert sand was done by culturing heterotrophic bacteria *microlive*® in parallel flasks containing 1.200 g of desert sand samples and 1.200 ml of the liquid medium *ekocomplex*®. Bioleaching consisted of exchanging fresh medium (1.000 ml) five times during incubation of the flasks under static conditions for 45 days at 21°C. The leachate was stirred to homogenise the solution before sampling. After centrifugation at 7.000 rpm for 15 minutes, the leachate was separated from the sample. The liquid supernatant was collected ten times (10 ml) for rapid elemental analyses of the bi-leaching experiment. The chemical abiotic controls were not given an inoculum but were otherwise incubated under similar conditions. The bioleaching experiments were performed in two replicates and the average values were recorded. The solution concentration data in the figures for each leachate sample is the average of three measurements. Redox potential and pH were measured with platinum and silver chloride electrodes (In-Lab Expert Pro, Mettler Toledo).

2.3 *Magnetic separation*

Dry electromagnetic separation was carried out using a laboratory high gradient magnetic separator with the induction of magnetic field at 1.3 T.

3 RESULTS AND DISCUSSION

3.1 *Bio-solution of sand quality improvement*

Desert sand consists mainly of rounded quartz grains covered with brown hematite films. The roundness of the desert sand particles is non-circular and subangular, and sub angularity is not uncommon. Smaller grains are more angular than larger ones, and there appears to be considerable variability between the roundness of the sand and the intensity of iron coverage (Figure 1A).

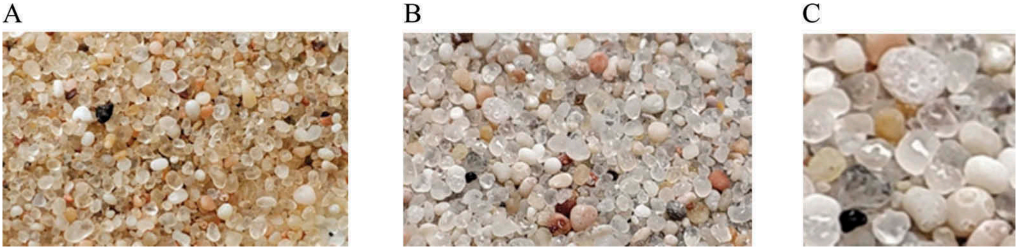

Figure 1. Grains of desert sand before (A) and after bioleaching (B), details of corrosive holes after bioleaching (C).

Desert sand from the Ardhuma deposit in Iraq was treated using growth culture solutions of the mould *Aspergillus niger* in combination with 10% HCl and a pH adjustment to 0.5 as an acidic biochemical leach to remove iron oxide contaminants. The Fe removal efficiency by biochemical leaching was 79.1% and the Fe_2O_3 content was 0.0125%. The combination of magnetic separation and biochemical leaching increased Fe removal to 85.8%, and Fe_2O_3 content was 0.0085%. Desert sand improved by biochemical leaching and magnetic deposition had a low iron oxide content and can therefore be used for optical applications, crystal glass, solar cells, and semiconductors (Mustafa et al. 2011).

Hydrochloric acid is an extremely aggressive chemical and must be handled and recycled safely. This process is not an ecological way of processing sand, so only the process of heterotrophic bioleaching with magnetic separation was tested to increase the quality of the raw material. The yield for the removal of each element is given in Table 4. The chemical analysis of the solid phase confirmed the significant removal of Fe, S, Mn of over 50% after bioleaching and the increase of Fe, S, Mn removal to over 65% after subsequent magnetic separation. The biogenic elements Cu, Zn, Ca were also removed during bioleaching with increasing Si content. These elements were found in the leachate and are important sources of nutrients (Fe, S, Mn, Zn, Ca, Cu) for plant stimulation. Quartz grains coated with hematite are biologically leached (Figure 1B), and corrosive holes are observed in some surfaces after clay detachment (Figure 1C).

Due to high melting temperatures and/or large waste streams from processing, about half of the desert sand samples studied contain more than 90 wt% silica, making it difficult to use as a raw material for glass, while sands with larger proportions of carbonates and/or feldspars form a melt at less than 1650°C when the SiO_2 content is less than 55 wt%. For desert sand glass with a thickness of 3 mm, a light transmittance of 85% at a wavelength of 550 nm has been demonstrated when the Fe_2O_3 content is less than 0.1 wt%, while for the same transmittance across the effective spectrum of silicon-based solar cells, the iron content needs to be further reduced (Minkels 2020).

Bioleaching with heterotrophic bacteria in static medium (Figure 2) in combination with magnetic separation resulted in an iron removal of 73.23%. The sand after treatment is suitable for the production of clear flat glass, coloured container glass, insulating glass fibres or ceramics and the liquid residue could support food production in desert states.

Figure 2. Desert sand leaching (A, 1 - abiotic control, 2 - bioleaching) and details desert sand color after 1 day of bioleaching (B) and after 1 months of bioleaching (C).

Table 4. The percentage of elements removal after bioleaching (BL) and magnetic separation (MS).

	BL		MS	
SAND	Content (mg/kg)	Yield (%)	Content (mg/kg)	Yield (%)
Al	6018	-23	2879	-63
Si	236,817	+14	213,804	+4
S	1675	-62	1500	-66
Ti	293	-38	247	-47
Fe	995	-62	707	-73
Mn	30	-51	20	-67
Ca	79,387	-19	88,268	-10
Cu	9	-31	11	-16
Zn	4	-41	0	-100

3.2 *Bio-solution of leachate utilization*

After each media change, the collected leachates contained different extracted biogenic elements K > Ca > S > Fe (Figure 3), except N (160 mg/l), P (11 mg/l), Na (517 mg/l) and Mg (46 mg/l), which are particularly important for plant health and development, by the media additions. In addition, organic acids (Table 5) and increased heterotrophic bacterial cells, mainly probiotic lactic acid bacteria (Table 6), were obtained from the leachates, which can be used for biostimulation of plants in conventional, organic or vertical agriculture.

Leachate has been registered by the FIBL Institute as *ekofertile™ plant* in the category of microbial biostimulants and biofertilizers for organic farming and has been confirmed to increase plant growth and yield by up to 100% and plant dry matter by 400% (Figure 4,5). The global market for biostimulants and biofertilizers has reached a value of €4 billion and is showing a strong growth trend. There is also a high demand due to the increasing production of organic food (increase of 89%).

Biofertilizers and biostimulants *ekofertile*™, produced by a new ecological process for leaching minerals by ekolive's bacteria *microlive*®, help by:

- Renewing soil microflora through plant growth promoting bacteria to increase nutrient bioavailability and uptake through nitrogen fixation and mobilisation of key nutrients, optimising soil structure and promoting root, flower and fruit growth and development, increasing crop yields, and eliminating toxic contaminants (oil, cyanides, phenols, pesticides, heavy metals, and other toxic substances) through the bioremediation effect.
- Naturally produced organic acids that strongly support plant development and growth and replace pesticides.
- Important micro and macro nutrients from dissolved natural minerals.

Desert soils and desert sands usually have high pH values. Such reactivity can have a negative impact on the availability of nitrogen, phosphorus, and micronutrients to plants, as

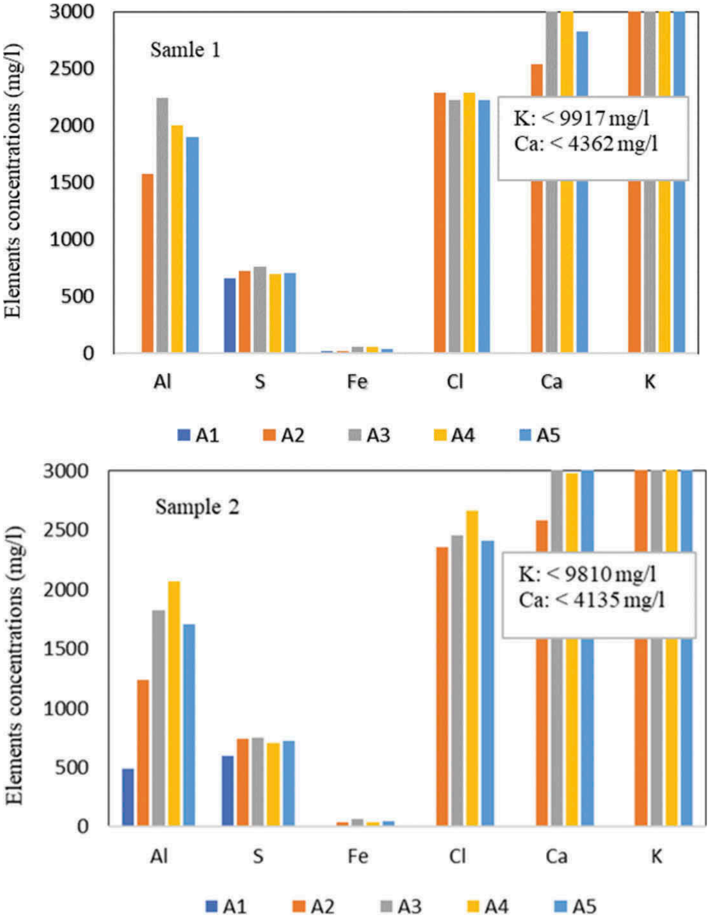

Figure 3. Chemical analyses (A1, A2, A3, A4, A5) of leachates during bioleaching of the desert sands in the parallel conditions (Sample 1, Sample 2).

Table 5. Concentration of organic acids in concentrated leachate by HPLC method.

	mg/L					
Sample	lactic acid	acetic acid	butyric acid	methanol	ethanol	propanone
Average concentration in concentrated leachate	20547.33	1327.23	221.97	688.62	0.00	822.41
Standard deviation	57.01	126.16	313.91	355.55	0.00	68.03

these are not in solution at pH > 7. The second problem with desert sand and soil is the lack of organic carbon. In the leachates, the pH dropped to 5.5 ± 0.5 after 4 days of bioleaching, and the admixture of organic matter in the medium contributed to the formation of organic acids, which can improve the availability of nutrients to plants.

The conversion of desert states into arable land is a global vision, and desert agriculture is a rapidly growing area of agriculture worldwide. In one of the best-known examples of organic desert farming in Sekem (Egypt), a drastic change in bacterial communities in the desert soil was observed after long-term farming (30 years). Bacterial communities in farmed soil showed

Table 6. Top species classification results of 16S Metagenomics analyse.

Class	Order	Genus	Species	num hits	%hits
Bacilli	Lactobacillales	Lactobacillus		60,478	45.442
Bacilli	Lactobacillales	Lactobacillus	Lactobacillus harbinensis (AB196123)	15,710	11.804
Bacilli	Lactobacillales	Lactobacillus	Lactobacillus diolivrans (AF264701)	8121	6.102
Bacilli	Lactobacillales	Leuconostoc		7006	5.264
Bacilli	Lactobacillales	Lactobacillus	Lactobacillus satsumsis (AB154519)	6877	5.167
Bacilli	Lactobacillales	Lactococcus		6569	4.936
Bacilli	Lactobacillales	Lactobacillus	Lactobacillus iwatensis (AB773428)	4079	3.065
Bacilli	Lactobacillales	Leuconostoc	Leuconostoc pseudomesenteroides (AB023237)	3473	2.610
Bacilli	Lactobacillales	Lactobacillus	Lactobacillus perolens (Y19167)	1733	1.302

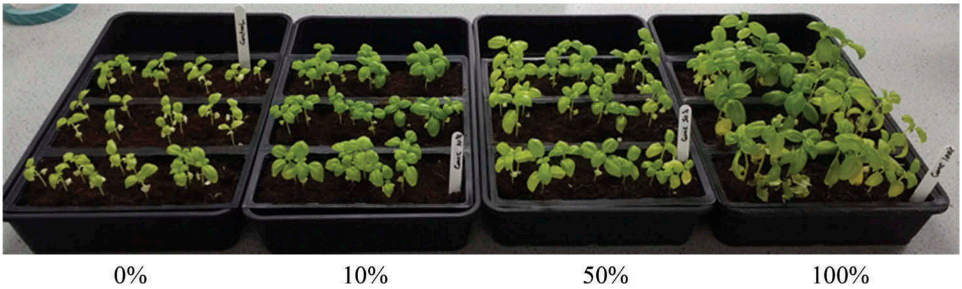

Figure 4. Used concentration of ekofertile™ and its effect on plant growth (BDC, England, 8 weeks).

higher diversity and better ecosystem function for plant health, but a loss of extremophilic bacteria. Firmicutes were significantly more abundant in the arable soil (37%) than in the desert sand (11%). Bacillus and Paenibacillus had identical 16S rRNA sequences in the amplicon library and isolate and accounted for 96% of the antagonists against phytopathogens. Compared to the desert sand, the proportion of antagonistic strains in the field was twice as high (21.6%/12.4%); the disease-suppressing bacteria were particularly enriched in the plant roots. On the other hand, several extremophilic bacterial groups such as *Acidimicrobium*, *Rubellimicrobium* and *Deinococcus-Thermus* disappeared from the soil after agricultural use. The N-fixing *Herbaspirillum* group was found only in desert soils. The abiotic factors of water supply and pH had a strong influence on the soil bacterial communities (Koberl et al. 2011).

The application of leachate with a pH of 5.5 ± 0.5 containing organic acids, macronutrients, micronutrients and lactic acid bacteria and their metabolites can help to increase crop yield and health. The accumulation of salt ions in the soil is due to high evaporation rates and low rainfall, and saline soils have serious consequences in terms of osmotic stress, ion toxicity and imbalance for desert-dwelling plants. Excessive amounts of sodium (Na^+) and chloride (Cl^-) ions have negative effects on plant membranes and enzymes, disrupting energy balance and protein metabolism (Shrivastava & Kumar 2015).

Bioleaching reduced the concentration of chloride (Cl^-) ions in the desert sand because the leachate contained these elements, which can be removed from solution by precipitation before the leachate is used for plant biostimulation.

4 CONCLUSION

The laboratory bioleaching experiment for iron removal with heterotrophic bacteria on desert sand were conducted to explore a simple cyclic operation for potential use at the industrial scale. The bioleaching test involved organic acid attack, resulting in the solubilization of Fe from the quartz surface and releasing biogenic elements to liquid residues. By this way it was possible to recover desert sand quality improvement and biofertilizer tested on basal. The bioleaching of desert sand by heterotrophic bacteria may be of commercial interest to glass, mining and agriculture industries.

Several studies have demonstrated the potential of biofertilizers to increase the yield and quality of various crops. However, market prices for low-value crops usually make the use of biofertilizers unprofitable.

Our solution offers the opportunity to solve two global problems at once. Improving the quality of silica sand by removing the main unwanted Fe impurities can be important for the future more versatile use of desert sand as a raw material for different industries. At the same time, biofertilizers with enormous value for future sustainable and safe food production are created.

Technology is currently under ecological technology verification ETV process, developed on TRL6 with the latest application on 150 and 300 tons of silica sand in the pilot operation in Slovenia. Biofertilizer from silica sand was tested on TRL5 on different crops (tomatoes, potatoes, herbs, strawberries, blueberries, bananas) and is listed in Dutch Organic Agriculture input list by FIBL institute as ekofertile™plant. Commercialization strategy is represented by licencing in desert states.

The biological solution to the two problems is another step towards a possible solution to the global sand crisis and sustainable agriculture in desert states.

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