

## A Bibliometric Analysis on Acidophilic Microorganism in Recent 30 Years

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### Abstract

**Objective:** To evaluate the global scientific research and the tendencies on acidophilic organism during the past 30 years. Studies in the acidophilic microorganism had significantly increased.

**Methods:** Articles related with the acidophilic organism were assessed by distribution of countries, institutes, journals using the method of bibliometric analysis.

**Results:** The results showed seven industrialized countries and four major developing countries were all listed in the top 20 most productive countries, which suggested economic conditions had an important effect on academic development. In addition, researchers in different institutions were more tending to cooperate. However, cooperation always occurred in the interior of the country. Through a synthetic analysis of the paper titles, author keywords and Keywords Plus, it revealed that "resistance to metal" attracted more attentions. Besides, this characteristic was also widely applied in bioleaching. At the level of research environment, "water" was the dominant position, such as acid mine drainage.

**Conclusions:** Study in the acidophilic microorganism had significantly increased. Cooperation had become the trend. Moreover, economic conditions had an important effect on academic development.

**Keywords:** Acidophilic microorganism; Bibliometric analysis; Resistance to metal; Bioleaching; Diversity

### Introduction

Many microorganisms survive in the physically and geo-chemically extreme conditions, which have challenged the limits of life. These conditions include extremes of temperature, pH, pressure, desiccation and others [1-3]. These microorganisms are termed as extremophiles. In recent decades, extremophiles have aroused great interest to researchers. Among them, acidophilic microorganisms are the ones that thrive in acidic environments with pH less than 3.0 [4,5]. They widely exist in acid mine drainage, bioleaching operation, and sulfuric hot spring [6-8]. Acidophilic microorganism not only can adapt to the environment of strong acid, but also can tolerate the high concentration of metal ions. Due to these special characteristics, they have been the hotspot in life science, and lots of microorganisms have been studied deeply, such as the *Acidithiobacillus ferrooxidans* [9]. Besides, acidophilic microorganisms have been widely applied in many respects, such as the bioremediation of heavy metal contaminated soil and water, extraction of enzyme, biohydrometallurgy and others [10-12].

Scientific articles on acidophilic microorganism have demonstrated a rapid increase over the past several decades. A number of papers presenting the latest research achievements have been published in authoritative scientific journals such as Nature and Science [13,14]. Despite the high growth rate of publications, there have been few attempts to gather systematic data on this special microorganism. A

common research tool for this analysis is the bibliometric method [15-17], which has already been widely applied in scientific production and research trends in kinds of topics, for example, global diversity [18], energy efficiency [19], agricultural technology [20], solid waste [21] biotechnology research [22,23]. The Science Citations Index Expanded (SCI-EXPANDED), from the Institute of Scientific Information (ISI) Web of Science databases, is the most important and frequently used source for a broad review of scientific accomplishment in all fields. Traditional bibliometric methods focus on citation and content analysis [24,25]. In recent years, analysis of word distribution of paper titles [26], KeyWords Plus [27], author keywords [28] in different periods has been used widely to get more information related to the research itself.

In this study, a bibliometric analysis of language, source country, institute and research field was performed to describe the importance of research on acidophilic microorganism. Besides, the distributions of keyword were also analyzed to study the research trends during the recent 30 years. Our conclusions not only provided a better understanding of global hotspot for researchers, but also clarified the future research direction on acidophilic microorganism.

### Data Sources and Methodology

Data used in this research were based on the online database of the SCI, retrieved from the ISI Web of Science, Philadelphia, USA. According to Journal Citation Reports (JCR), it indexed 7391 major journals with citation references across 173 scientific disciplines in 2011. Besides, the reported impact factor (IF) of each journal was

acquired from the 2011 JCR. Here, five search terms, including: "acidophilic organism", "acidophilic microorganism", "acidophilic bacteria" "acidophilic fungi" "acidophilic archaea" were used as keywords to search titles, keywords, document types, addresses and others during 1983-2012. Articles from England, Scotland, Northern Ireland and Wales were reclassified into the UK, and articles originating from Hong Kong and Taiwan were included in China. The collaboration type was determined by the addresses of the authors. The single-country publication was classified if the addresses of authors were in the same country. On the contrary, the internationally collaborative publication was assigned if authors were from different countries. In the same way, the single-institute publication was assigned if the addresses of researchers were from the same institute. The inter-institutionally collaborative publication was assigned if authors were from multiple institutes.

The words in titles were separated, and then conjunctions and prepositions such as "and", "the", "or", "for", "with", "by", and "on" were discarded, as they were meaningless in the further analysis. The ranks and frequencies of keywords between 1983 and 2012 were calculated in order to thoroughly analyze the variations of trends.

## Results and Discussion

### Characteristics of publication outputs

In this study, 10 document types were contained in the 2199 publications during the 30-year study period, in which article was the most frequent type. Articles contributed a significant portion, 85% or 1873 of the total production. Another two documents were less significant, including proceedings paper (6.5%) and review (4.9%). The devotion of others was rare. As the dominant type of document, articles were used for further analysis. Ninety-eight percent of the journal articles were written in English. Another 12 languages also appeared. However, the proportion was less than 1%. Obviously, English was the dominant language in acidophilic microorganism research.

The number of both of SCI documents and articles was analyzed and performed respectively in Figure 1 to understand the research trend in the 30 years. World academic publications had a notable growth after 1990, and there were two notable increases in the past three decades (1990, 2003). One important reason was that United States proposed the concept of the human genome in 1985, and in 1990 the 3-billion dollars project was formally founded. "Human Genome Project" intended to complete the entire human genome DNA sequence analysis in 15 years [29]. As a result, high-speed DNA sequencing methods came into being, which encouraged the study in microorganism on molecule level. Subsequently, high demand for low-cost sequencing had driven the development of high-throughput sequencing and several new methods for DNA sequencing were developed [30]. These techniques comprised the first of the "next-generation" sequencing methods, which was applied in many studies. Such as massively parallel signature sequencing (MPSS) published and marketed in 2000, 454 Life Sciences marketed in 2004 [31].

Based on the classification of subject categories in JCR 2011, the publication output data of acidophilic microorganism research were distributed into 109 SCI subject categories during 1983-2012. The most significant category was "Microbiology" (20%), followed by "Biotechnology and Applied Microbiology" (13%), "Biochemistry and Molecular Biology" (8.2%) and "Environmental Sciences" (3.9%).

"Microbiology" and "the Biotechnology and Applied Microbiology" were the two fastest growing subject categories, especially after 2001 (Figure 2), suggesting that the value of microorganism had been applied to the practice of production gradually, and molecular technology had been widely used in the study.

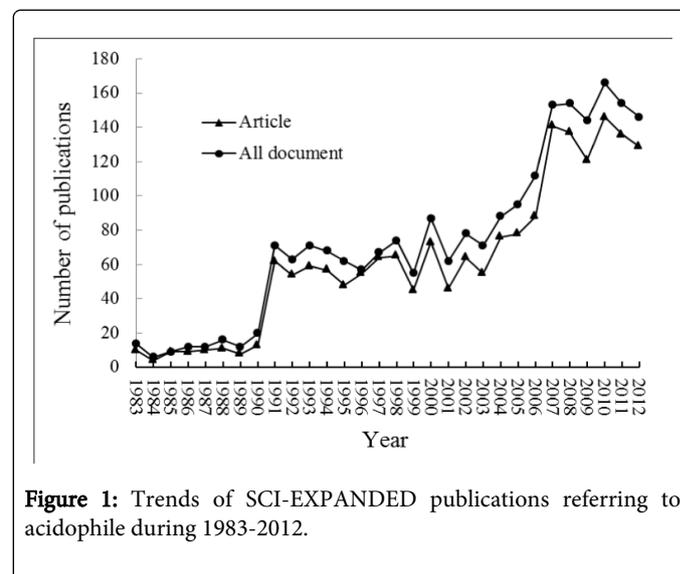


Figure 1: Trends of SCI-EXPANDED publications referring to acidophile during 1983-2012.

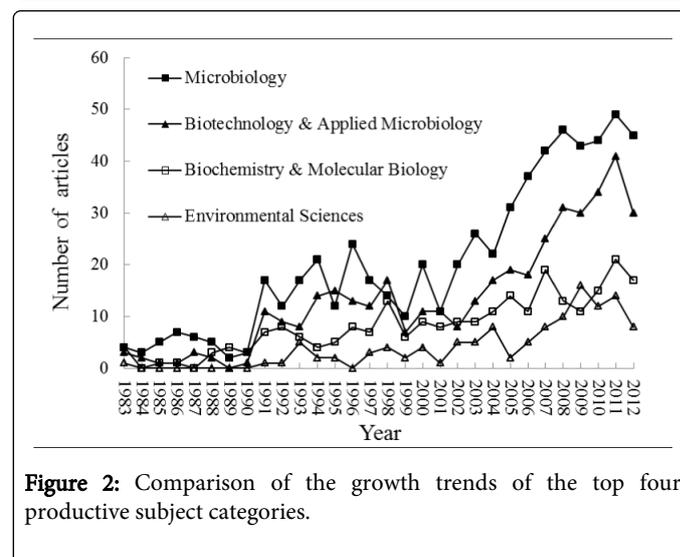


Figure 2: Comparison of the growth trends of the top four productive subject categories.

Articles were published in lots of journals, and the top 20 most productive journals were summarized in Table 1. In this special study field, Applied and Environmental Microbiology published the most articles with (107; 5.7%), followed by International Journal of Systematic and Evolutionary Microbiology with (62; 3.3%), Hydrometallurgy with (48; 2.6%). The average citation rate of journals in acidophilic microorganism was the most direct evidence for indicating the impacts of journal: the higher the citation was, the greater the impact was in this field. Besides, the average cited reference number per article also showed the importance of each article. International Journal of Systematic and Evolutionary Microbiology had the highest citation rate among the 20 journals. And Environmental Microbiology shared the highest average cited reference and the supreme IF. Those manifested the significant position of the two journals in this field.

Journal	TP	TP (%)	IF	TC	TC/TP	NR	NR/TP
Applied and Environmental Microbiology	107	5.7	3.829	3647	34.1	4218	39.4
International Journal of Systematic and Evolutionary Microbiology	62	3.3	2.268	2127	34.3	2158	34.8
Hydrometallurgy	48	2.6	2.027	511	10.6	1427	29.7
Extremophiles	47	2.5	2.941	677	14.4	1647	35
Journal of Bacteriology	35	1.9	3.825	732	20.9	1012	28.9
Microbiology	35	1.9	0.718	99	2.8	657	18.8
FEMS Microbiology Letters	35	1.9	2.044	649	18.5	643	18.4
Bioresource Technology	24	1.3	4.98	189	7.9	777	32.4
Environmental Microbiology	23	1.2	5.843	723	31.4	1210	52.6
Archives of Microbiology	20	1.1	1.431	299	15	623	31.2
Geomicrobiology Journal	20	1.1	2.017	313	15.7	839	42
World Journal of Microbiology & Biotechnology	18	1	1.532	113	6.3	457	25.4
FEMS Microbiology Ecology	18	1	3.408	508	28.2	734	40.8
Systematic and Applied Microbiology	17	0.9	3.366	469	27.6	495	29.1
Canadian Journal of Microbiology	17	0.9	1.363	197	11.6	560	32.9
Minerals Engineering	16	0.9	1.352	227	14.2	449	28.1
Microbiology-Sgm	16	0.9	3.061	496	31	771	48.2
Bioscience Biotechnology and Biochemistry	15	0.8	1.276	312	20.8	454	30.3
Microbial Ecology	14	0.7	2.912	162	11.6	673	48.1
Biotechnology and Bioengineering	14	0.7	3.946	268	19.1	411	29.4

**Table 1:** The top 20 most productive journals based on the total number of articles. Note: TP: total number of articles, IF: 2011 ISI Impact factor, TC: total citation count, NR: cited reference count, TC/TP: average of citations in a paper, and NR/TP: the average cited reference count per article.

### Distribution of country articles

All articles with author addresses could be used to analyze the distribution of country. In 1725 articles with author addresses, 71.6% were single-country publications, and only 28.4% were international. The top 20 most productive countries were summarized in Table 2, ranking with the way of number of journal articles and total citations. Among the 20 countries, the USA was the most productive country, including both single-country articles (214) and internationally collaborative articles (135). Germany ranked second with 201 and Japan ranked third with 190. Economic condition was related to the academic achievement: the seven industrialized countries (G7 group: the USA, Germany, Japan, France, the UK, Canada, and Italy) and four major developing countries (“BRIC”: China, India, Brazil, and

Russia) were all included in the top 20 countries [32]. The same phenomenon was revealed in other bibliometric analyses [33,34]. Apart from the economic condition of different countries, one typical acid mine drainage located in USA, Iron Mountain Mine. As one of America's most toxic waste sites, it had been listed as a federal Superfund site since 1983, which made it be one research hot spot [35,36]. Between position of the “G7 group” and “BRIC”, Spain was another high-producing country, because another typical acid mine drainage, Tinto River, which was notable for being very acidic (pH 2) and its deep reddish hue, was located in Spain [37,38]. Another important message from these data in Table 2 was that single-country articles were the main trend in the study of acidophilic microorganism, especially in Japan, with a percentage of 90%.

Country	TP	SP	SP (%)	TC	TC/SP	CP	CP (%)	TC	TC/CP
USA	349	214	61.3	7487	35	135	38.7	2649	19.6
Germany	201	104	51.7	2141	20.6	97	48.3	2478	25.5

Japan	190	171	90	2463	14.4	19	10	279	14.7
China	158	118	74.7	676	5.7	40	25.3	459	11.5
UK	152	81	53.3	2175	26.9	71	46.7	1658	23.4
Spain	138	95	68.8	1546	16.3	43	31.2	570	13.3
Russia	97	51	52.6	253	5	46	47.4	1474	32
France	87	48	55.2	1128	23.5	39	44.8	750	19.2
Canada	81	54	66.7	942	17.4	27	33.3	402	14.9
India	81	65	80.2	855	13.2	16	19.8	68	4.3
Italy	62	41	66.1	673	16.4	21	33.9	417	19.9
Chile	54	27	50	391	14.5	27	50	391	14.5
Australia	46	21	45.7	350	16.7	25	54.3	311	12.4
Netherlands	40	20	50	509	25.5	20	50	295	14.8
South Korea	38	18	47.4	158	8.8	20	52.6	154	7.7
Sweden	35	13	37.1	284	21.8	22	62.9	313	14.2
Brazil	33	26	78.8	113	4.3	7	21.2	103	14.7
South Africa	30	19	63.3	305	16.1	11	36.7	205	18.6
Finland	25	10	40	98	9.8	15	60	112	7.5
Belgium	21	11	52.4	107	9.7	10	47.6	130	13

**Table 2:** Top 20 most productive countries based on the total number of articles. Note: TP: total number of articles, SP: single country articles, CP: internationally collaborative articles, TC: total citation count.

### Distribution of institute analysis

The distributions of different institutes were evaluated by the affiliation of at least one author. Of all articles with author addresses, 43.2% were single-institute articles and 56.8% were inter-institutionally collaborative articles, suggesting that study of acidophilic microorganism called for teamwork among institutes. The top 20 most productive institutes were summarized in Table 3, in which the distribution was equal. Three were from China, the USA, the UK, Spain, two were from Russia, and one was from Germany, Japan, France, Sweden, India, Chile. The Russian Academy of Sciences had the most total articles (94), including 12 independent articles and 82 inter-institutionally collaborative articles, followed by Central South University, University of California, Berkeley, University of Chile and two institutes from Spain, Spanish National Research Council and the University of Murcia. It should be noted that

University of California, Berkeley had the highest average citation rate, including independent articles (238) and inter-institutionally collaborative articles (35.6). It suggested that University of California, Berkeley had a fairly high status in this academic field. It should be noted that the university was close to the typical acid mine drainage, Iron Mountain Mine, which was mentioned above. Another observation could be obtained from Table 3 that only four institutes (2 UK, 1 Spain, 1 India) had more independent articles than inter-institutionally collaborative articles. There were also another two institutes, Oak Ridge National Laboratory and Max Planck Institute for Terrestrial Microbiology that only published the inter-institutionally collaborative articles. Moreover, the average citation rate was relatively high. These proved that the academic communities of acidophilic microorganisms were more tending to cooperation.

Institute	TP	SP	SP (%)	TC	TC/SP	CP	CP (%)	TC	TC/CP
Russian Academy of Sciences, Russia	94	12	12.8	118	9.8	82	87.2	1551	18.9
Central South University, China	48	11	22.9	75	6.8	37	77.1	158	4.3
University of California, Berkeley, USA	42	4	9.5	952	238	38	90.5	1351	35.6
University of Chile, Chile	39	7	17.9	107	15.3	32	82.1	505	15.8

Spanish National Research Council, Spain	39	9	23.1	242	26.9	30	76.9	15	0.5
The University of Murcia, Spain	36	20	55.6	578	28.9	16	44.4	164	10.3
Chinese Academy of Sciences, China	36	7	19.4	29	4.1	29	80.6	102	3.5
Okayama University, Japan	27	13	48.1	142	10.9	14	51.9	242	17.3
Autonomous University of Madrid, Spain	26	4	15.4	46	11.5	22	84.6	313	14.2
University of Warwick, UK	25	14	56	491	35.1	11	44	425	38.6
Umea University, Sweden	24	5	20.8	144	28.8	19	79.2	212	11.2
Lomonosov Moscow State University, Russia	24	8	33.3	19	2.4	16	66.7	166	10.4
National Centre for Scientific Research, France	23	8	34.8	199	24.9	15	65.2	323	21.5
The University of Wales, UK	22	16	72.7	440	27.5	6	27.3	228	38
Indian Institute of Chemical Technology, India	22	20	90.9	580	29	2	9.1	16	8
Bangor University, UK	21	7	33.3	71	10.1	14	66.7	134	9.6
The Ohio State University, USA	19	2	10.5	54	27	17	89.5	161	9.5
Chinese Academy of Agricultural Sciences, China	19	1	5.3	12	12	18	94.7	182	10.1
Oak Ridge National Laboratory, USA	18	—	—	0	—	18	100	398	22.1
Max Planck Institute for Terrestrial Microbiology, Germany	16	—	—	0	—	16	100	1181	73.8

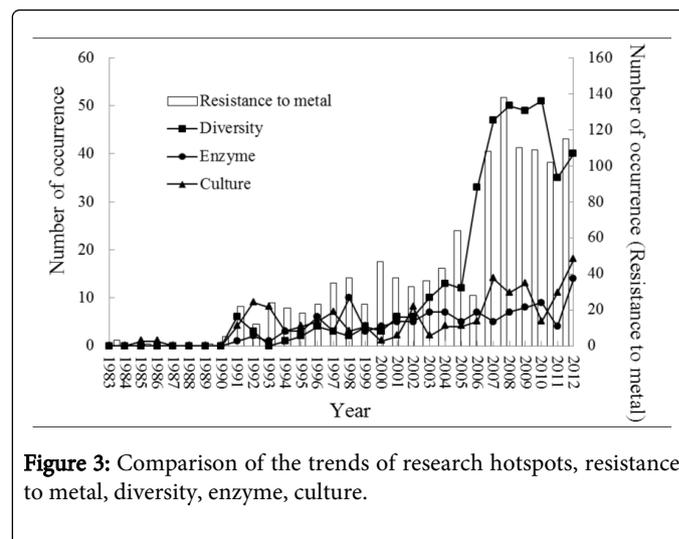
**Table 3:** Top 20 most productive institutes based on the total number of articles. Note: TP: total number of articles, SP: single institute articles, CP: inter-institutionally collaborative articles, TC: total citation count, —: no articles.

### Hot issues

The most important information, which the author expected to express to readers, was presented in the title, keywords and KeyWords Plus. In order to analyze the three separated parts synthetically, the synonymic single words and congeneric phrases were summed and grouped into categories. In this way, the analysis of historical development of science could be more complete and precise, and the new direction about this field could be found. A new method named “word cluster analysis” had been applied to analyze the research trends in risk assessment [39] and nitrate removal. All words included in Figures 3 and 4 contained their plural forms and other transformations, as well as words with the similar meanings.

Research trends in acidophilic microorganism were separated into two categories: research hotspot and research environment. In terms of the research hotspot, the “resistance to metal” was the most predominant for 20 years (Figure 3). Tolerance to various kinds of heavy metal had been analyzed in recent years, such as Fe, Cu, Al, Zn. This characteristic had been widely applied to bioleaching to increase the purity of mixed ore [40-42]. In addition, “diversity” became the second research branch with a fast speed, since the application of cultivation-independent molecular techniques becoming more mature, such as FISH, PCR-DGGE [43,44]. The number of the articles using molecular biology techniques during 2005-2012 was half of the total number in 30 years. On the contrary, because of the limitation of technical means and the difficulty in controlling the micro-world, the development of “enzyme” and “culture” was relatively slow. Therefore, the study in acidophilic microorganism focused on the resistance to

metal and diversity, which had more practical value and substantial benefit.



**Figure 3:** Comparison of the trends of research hotspots, resistance to metal, diversity, enzyme, culture.

Research trend of kinds of environments had been showed in Figure 4, including “water”, “soil”, “hot spring” and “leaching heap”. The difference between four environments became obvious after 2006, because of a rapid increase in the “water” and “bioleaching heap”. First of all, “water” was the most wide study environment, such as acid mine drainage. The research in “water” reached a peak point in 2008. Referring to the increasing trend of “bioleaching heap”, the main

reason was that people realized the value of acidophilic microorganism in industry. France was the earliest one, trying to leaching gold in ores by bacteria in 1964, and achieved encouraging results. Subsequently, bioleaching developed gradually, and became industrialized. The industrialization reached an obvious peak point in 2008. Although “soil” was not main living environment, acidophilic microorganism was abundant in soil which was proved in lots of articles. The field around the acid mine drainage was contaminated by the acid water, and became exclusively suitable for this special microorganism. On the contrary, “hot spring” acted as the original living environment, but articles about “hot spring” were rare.

Another result should be noted that there was a decrease after 2007, including “water”, “bioleaching heap”, “soil”, and even “resistance to metal”, “diversity”. All of this may be a direct result of economic crisis happened in 2007, which made the fund for scientific research have an obvious shrinkage in the whole world. To a large extent, the economic situation provided a solid foundation to the research.

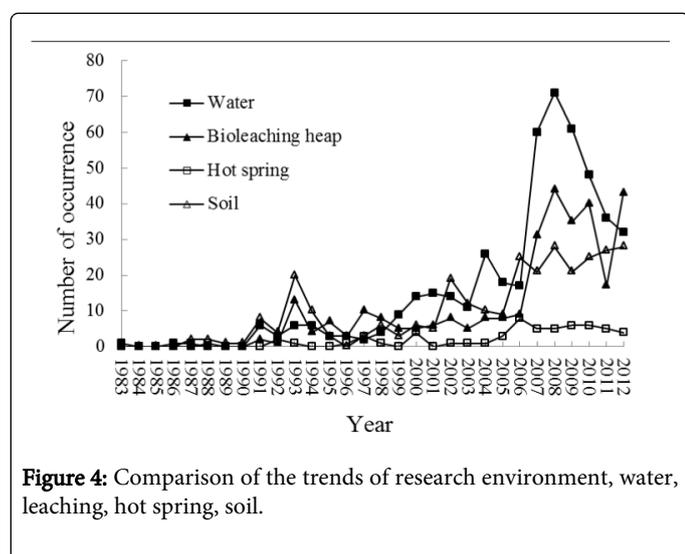


Figure 4: Comparison of the trends of research environment, water, leaching, hot spring, soil.

## Conclusions

Based on the databases of acidophilic microorganism listed in SCI-EXPANDED, some significant points on the worldwide research performance were studied using bibliometric analysis during the 30 years. The following conclusions were summarized from this study:

Study in the acidophilic microorganism had significantly increased in the last 30 years, especially in the year 2003-2012.

1873 articles have been distributed into 109 SCI subject categories. “Microbiology” and “the Biotechnology and Applied Microbiology” were the two fastest growing subject categories, suggesting that the value of microorganism had been applied to the practice of production gradually.

At the country level, 71.6% were single-country publications, and 28.4% were international articles. The USA had the most dominant position including the most total articles, single-country articles and internationally collaborative articles. Besides, economic condition was related to the academic achievement. The G7 and the BRIC were listed in the top 20 most productive countries.

In the analysis of distribution of institute, 43.2% of all articles were single-institutional and 56.8% were inter-institutional. In the top 20

most productive institutes, only four institutes had more independent articles than inter-institutionally collaborative articles, and another two institutes only published the inter-institutionally collaborative articles. These proved that the academic communities of acidophilic microorganisms were more tending to cooperation.

Using a new bibliometric method - “word cluster analysis” - found that “resistance to metal” and “diversity” will continue to be the leading research hotspots. Eventually, “water” will be the main research environment.

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