Algal Research 60 (2021) 102527

Contents lists available at ScienceDirect

Algal Research

journal homepage: www.elsevier.com/locate/algal

Review article

Early US-Japan collaborations in algal biofuels research: Continuities and perspectives

Kimi Coaldrake

Pan Pacific Technologies Pty Ltd, 9 Church Road, Paradise, SA 5075, Australia

ARTICLE INFO

Keywords:
Microalgae
Algal biofuels
Collaborations
1950s
United States
Japan

ABSTRACT

Algal research for the development of large-scale production of biofuels in open ponds is often believed to have started in the US as part of the Department of Energy's Aquatic Species Program in the early 1980s. Little attention, however, has been paid to earlier algal research collaborations between the US and other countries, particularly Japan. These collaborations include US algal research in the 1950s under the visionary leadership of scientist/politician Vannevar Bush (1890–1974) that strategically built upon Japanese efforts led by the microbiologist Hiroshi Tamiya (1903–1984). Unpublished reports and correspondence held in archives in the Smithsonian Museum and the Carnegie Institute of Washington became available to the author. They shed new light on these collaborations. This article uses these documents and more recent sources to review events associated with Bush inviting Tamiya to visit the US in 1952 to collaborate with American scientists at the Carnegie Institution and elsewhere even while Japan was still under US/Allied Occupation. These interactions continued during the 1950s. Articles, reports on experimental results and Tamiya's observations of algal research in the US, Europe and Asia found among the sources are still pertinent. Furthermore, Tamiya's successful mass outdoor culture of algae, particularly *Chlorella*, in a pilot plant in Japan in the 1950s that became commercially successful had productivities on a par with results reported in the US as recently as 2018. However, while lessons were learned from early collaborations between the US and Japan, many have been subsequently overlooked. There are lessons to be learned from these early US-Japan collaborations that draw attention to pioneering algal research and the need to maintain archives. They also reveal critical continuities and provide perspectives on current algal biofuels research.

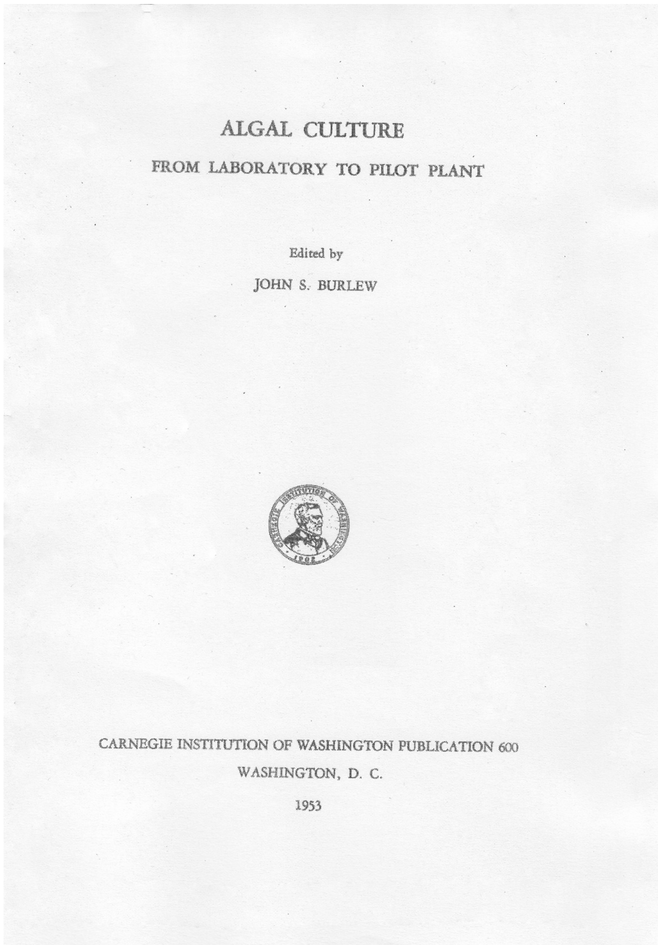
1. Introduction

Algal Culture: From Laboratory to Pilot Plant, was published on July 15, 1953 by the Carnegie Institution of Washington [1], now known as the Carnegie Institute for Science (hereafter the Carnegie Institution) (Fig. 1). This monograph predates by up to 60 years the reports often cited as milestones in algal research, namely, the Aquatic Species Program (Closeout Report) [2], the National Algal Biofuels Technology Roadmap [3] and the National Alliance for Algal Biofuels and Bio-Products Final Technical Report (NAABB) [4]. Some researchers, for example, Becker [5] acknowledge it as an important text for the early large-scale cultivation of microalgae. Borowitzka [6] notes that it presents the state of the field for work done in the US, Germany, Japan and Israel. The monograph is still available in university libraries and online through the Carnegie Monograph Series [1].

The monograph captures the accumulated knowledge of leading international scientists on algae, particularly *Chlorella*, immediately after World War II to the early 1950s as they debated the economic feasibility of the large-scale cultivation of algae. The Foreword was written by Vannevar Bush, President of the Carnegie Institution from 1938 to 1955. He describes the events leading to the monograph's publication and acknowledges the work done in the Department of Plant Biology of the Carnegie Institution. He also notes the contribution of three chapters by a Japanese scientist, Hiroshi Tamiya, from the Tokugawa Institute for Biological Research (Tokugawa Seibutsu Kenkyūjo) in Tokyo (hereafter the Tokugawa Institute). The contribution of this publication to the field of phycology in general and microalgae in particular, and the relevance of its conclusions today, is often overlooked. The role of Bush and the influence of Tamiya's research on the US algal research program in the 1950s are also rarely discussed. This article focuses attention on the monograph as a lens through which to understand collaborations between the US and Japan on algal biofuels research in the early 1950s with particular attention to the significant contributions of Bush and Tamiya.

E-mail address: coaldrake@panpacific.com.au.

https://doi.org/10.1016/j.algal.2021.102527
Received 18 August 2021; Received in revised form 20 September 2021; Accepted 2 October 2021
Available online 21 October 2021


ALGAL CULTURE

FROM LABORATORY TO PILOT PLANT

Edited by

JOHN S. BURLEW

CARNEGIE INSTITUTION OF WASHINGTON PUBLICATION 600

WASHINGTON, D. C.

1953

Fig. 1. The title page of John S. Burlew, ed. Algal Culture: From Laboratory to Pilot Plant, The Carnegie Institution of Washington DC, 1953.

Research for this article began by reviewing the monograph and scientific literature, including articles in the Carnegie Institution of Washington Year Books [7] and Studies from the Tokugawa Institute [8]. As an ethnographic study, it also uses a wide range of sources for detailed descriptions, analyses of events and discussion of practices associated with the collaborations essential to this review article. The author found Primary documents written in English and Japanese in archives at the Carnegie Institution, the Smithsonian Institution, the Tokugawa Institute, the University of Tokyo and the Bradbury Science Museum (Los Alamos). Such primary documents are part of the 'hidden world' beyond internet sources, found in institutions, national laboratories, researchers' offices and computer storage drives. In some instances, the author saved documents from destruction. They include correspondence with handwritten annotations, unpublished reports, administrative memos and photographs related to the early US and Japanese algal research collaborations. [Appendix A] They document an astonishingly productive period in scientific history in the decade immediately after the end of World War II when a series of unlikely events culminated in collaborations between the US and Japanese scientists and the monograph publication. Selected documents from the author's collection are integrated into the review. Supplementary materials provide further information on the primary sources. They remain relevant to current biofuels research especially relating to the mass culture of algae.

The following section presents a brief historical overview of algal research in the US and Japan to the 1950s as the context for the collaborations. It introduces Vannevar Bush and Hiroshi Tamiya as the key figures in these developments and how they were brought together. Section 3 focuses on the significant outcomes of the collaborations in the 1950s including the monograph's publication, visits by Tamiya to US institutions and European algal programs, and Tamiya's research into the mass culture of algae. Section 4 provides perspectives on selected developments in algal biofuels research in the US and Japan since 1957 to highlight the ongoing impact of the 1950s events. Conclusions identify continuities and perspectives relevant to current algal research. Throughout the review article, Japanese names are written in Western order with family names last.

2. A brief overview of the US and Japanese algal biofuels research leading to the 1950s collaborations

Discussion of pioneering work that laid the foundation for algal biofuels in the US and the early research in other countries such as Germany [9] is found in Borowitzka's excellent short history of energy from microalgae [6]. Attention turns in this section to developments in algal research in Japan and the US as part of the pathway that led to the early collaborations between these two countries.

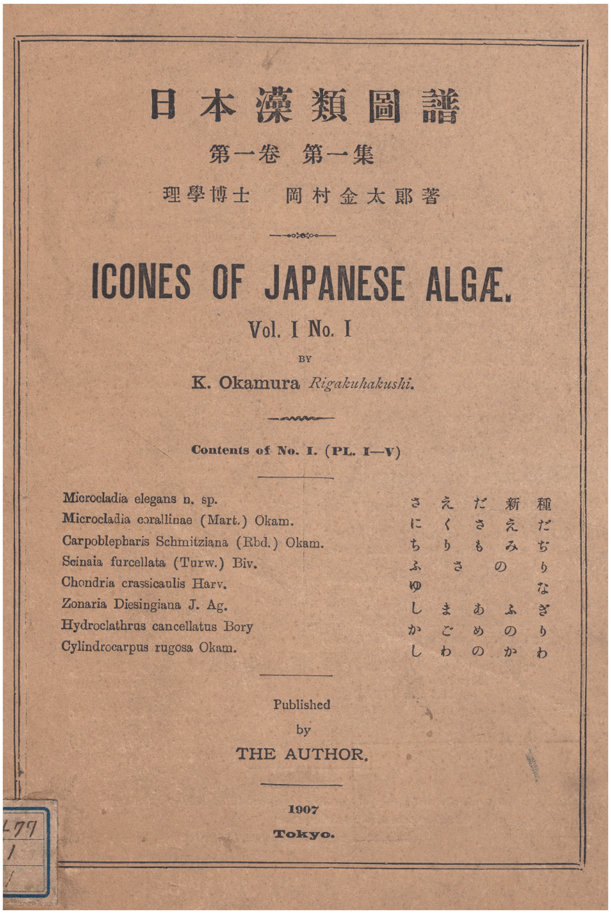
2.1. A brief overview of research leading to algal biofuels in the US and Japan in the 1950s

Algal research in Japan began in 1889 at the Botany Department of Tokyo Imperial University (later known as the University of Tokyo). The first professor of botany, Ryokichi Yatabe, started the department's algae collection at this time. His student, Kintarō Okamura, the founder of phycology in Japan, classified approximately 1000 species of macroalgae [10]. He was responsible for publishing this research in the six volumes of *Japan Seaweed Illustrated* (*Nippon Kaisō Kyōkai*) (1900–1902) and the seven-volume, *Icones* [sic.] *of Japanese Algae* (*Nihon sōrui zufu*) (1907–1942) [11] (Fig. 2).

The Tokugawa Institute was established in 1918 by Yoshichika Tokugawa. The Tokugawa clan were the shoguns of Japan from 1603 to 1868. They remained an influential dynasty providing philanthropic support for sciences, especially biology and the arts, in the 20th century [12]. Tamiya joined the Botany Department of Tokyo Imperial University and the Tokugawa Institute in 1926. At this stage, Tamiya and colleagues at the Tokugawa Institute were primarily using algae for experiments on photosynthesis [13,14]. Tamiya's first article about algae was published in 1934, discussing the role of the cytochrome Peroxidase in different species of algae and the research that had gone before it [15].

World War II, perhaps predictably, was the catalyst for the research into microalgae as a source for lipids for fuels or food rather than as a base material for studying photosynthesis. By the late 1930s, Japan was already at war with China to secure access in Asia to raw material reserves and other economic resources, specifically food, fuel and labor. By the end of the Pacific war, algal research had advanced. It was only in the late 1940s and early 1950s that Tamiya and colleagues turned their attention more extensively to the larger-scale culture and engineering requirements suitable for fuel and food [16], as reported in the monograph.

Parallel to these developments, scientists at leading US institutions in the 1930s also conducted algal research. For example, Robert Emerson and William Arnold of the Kerckhoff Laboratories of Biology at the California Institute of Technology used algae, particularly *Chlorella*, to study the effects of photosynthesis in alternating periods of light and dark [17]. By comparison, Bostwick Ketchum and Alfred Redfield, from the Woods Hole Oceanographic Institution and the Biological Laboratories of Harvard University, studied methods for maintaining a continuous supply of diatoms in culture [18]. Algal research in the US gained momentum from 1941. For example, scientists at the Department of Plant Biology of the Carnegie Institution investigated the photosynthesis of higher plants such as grasses, algae and other diatoms [19]. By


日本藻類圖譜

第一巻　第一集

理學博士　岡村金太郎著

ICONES OF JAPANESE ALGÆ.

Vol. I No. I

BY

K. Okamura *Rigakuhakushi.*

Contents of No. I. (PL. I—V)

Microcladia elegans n. sp.	さえだ新種
Microcladia corallinae (Mart.) Okam.	にくさえだ
Carpoblepharis Schmitziana (Rbd.) Okam.	ちりもみぢ
Scinaia furcellata (Turw.) Biv.	ふさのり
Chondria crassicaulis Harv.	ゆな
Zonaria Diesingiana J. Ag.	しまあふぎ
Hydroclathrus cancellatus Bory	かごめのり
Cylindrocarpus rugosa Okam.	しわのかわ

Published

by

THE AUTHOR.

1907

Tokyo.

Fig. 2. The cover of Volume 1 of the seven-volume *Icones* [sic.] of *Japanese Algae* (1907–1942) on macroalgae classified by Kintarō Okamura from the Botany Department of Tokyo Imperial University (later the University of Tokyo).

1942 they began to focus on *Chlorella* and culturing it for their photosynthesis experiments [20]. In 1943 their work with algae turned to subjects of possible importance to the war effort. Rather than focusing on algae as a potential source of food or fuel at this stage, they began to research the production of an antibiotic, chlorellin, from *Chlorella* [21–23], but results were inconclusive.

After World War II, US scientists shifted investigations more firmly to algae as a potential food and fuel source. The Department of Plant Biology of the Carnegie Institution discovered that different environmental factors could influence photosynthesis to produce variation in the chemical composition, such as lipids, found in each plant [24]. Between 1947 and 1948, they considered the potential food source of algae, particularly *Chlorella* [25], because it could be grown under controlled conditions. The Carnegie Institution decided that the production of Chlorella on a large scale for the possible production of food [26] warranted more investigation. They contracted the Stanford Research Institute under the sponsorship of the Research Corporation to undertake a lab-scale study to see if it was feasible to produce *Chlorella* on an industrial scale [27,28]. They discovered that more work was needed for it to be economical. More research into the large-scale culturing of *Chlorella*, therefore, commenced in February 1951 when Arthur D. Little Inc. set up a large-scale *Chlorella* pilot plant in Cambridge, Massachusetts. At the time, scientists at the Department of Plant Biology were also investigating the feasibility of smaller pilot plants. After the large pilot plant in Cambridge was built, the scientists used these smaller plants to study the effects of intermittent light and the use of brighter light to achieve greater photosynthetic efficiency.

2.2. Vannevar Bush and Hiroshi Tamiya: the key figures and how they came together

This section discusses the two key figures, Vannevar Bush and Hiroshi Tamiya who played pivotal roles in the collaborations and the unlikely circumstances that brought them together. While the National Academy of Sciences has published detailed biographies with extensive bibliographies for Bush [29] and Tamiya [30], the primary documents reviewed here provide additional details that help understand the early US-Japan collaborations.

2.2.1. Vannevar Bush (1890–1974)

According to the principal biographer of Vannevar Bush, “No American has had greater influence in the growth of science and technology.” (p. 89) [29] (Vannevar Bush is not related to Presidents Bush.) He received his doctorate in engineering from the Massachusetts Institute of Technology) in 1916 [31]. By 1930 Bush's reputation was growing. He became Dean of the School of Engineering and Vice President of MIT in 1937. In 1938 he accepted the position as President of Carnegie Institution of Washington, holding the position until 1955. He was a member of the Joint New Weapons Committee of the Joint Chiefs of Staff. When the Manhattan Engineering District was created, Bush served as Chairman of its Military Policy Committee, which functioned as its Board of Directors [29] (Fig. 3). He was an official observer of the nuclear bomb test with Oppenheimer at the Trinity site.

Although Bush was a significant player in the scientific side of World War II, he is not as well-remembered because his name is often not included even when his administrative role is listed in documents. For example, his name is unlisted in the organizational chart of the Manhattan Project (Fig. 4. At the top of the chart, the Military Policy Committee headed by General Groves with the Director and the Governing Board written below. Names of the Board members, including Bush, are not listed. The Administration section is below, presented on the left side of the chart with the names and roles. By comparison, on the right side of the chart, the project's four divisions (Engineering, Chemistry, Physics and Theoretical) are noted, including the names of scientists such as Nils Bohr and Enrico Fermi. These well-known names are found in textbooks even today.

Bush also worked behind the scenes in the development of algal research at the Carnegie Institution. The newly discovered documents show that he worked with Paul Scherer (Executive Officer of the Carnegie Institution based in Washington D.C.) and Stacy French (Director of the Department of Plant Biology based at Palo Alto, California) and

Fig. 3. A photograph taken at Hanford, Washington in 1942 shows (left to right): Vannevar Bush, James Conant, Major General Leslie Groves and Colonel Franklin Matthias [32].

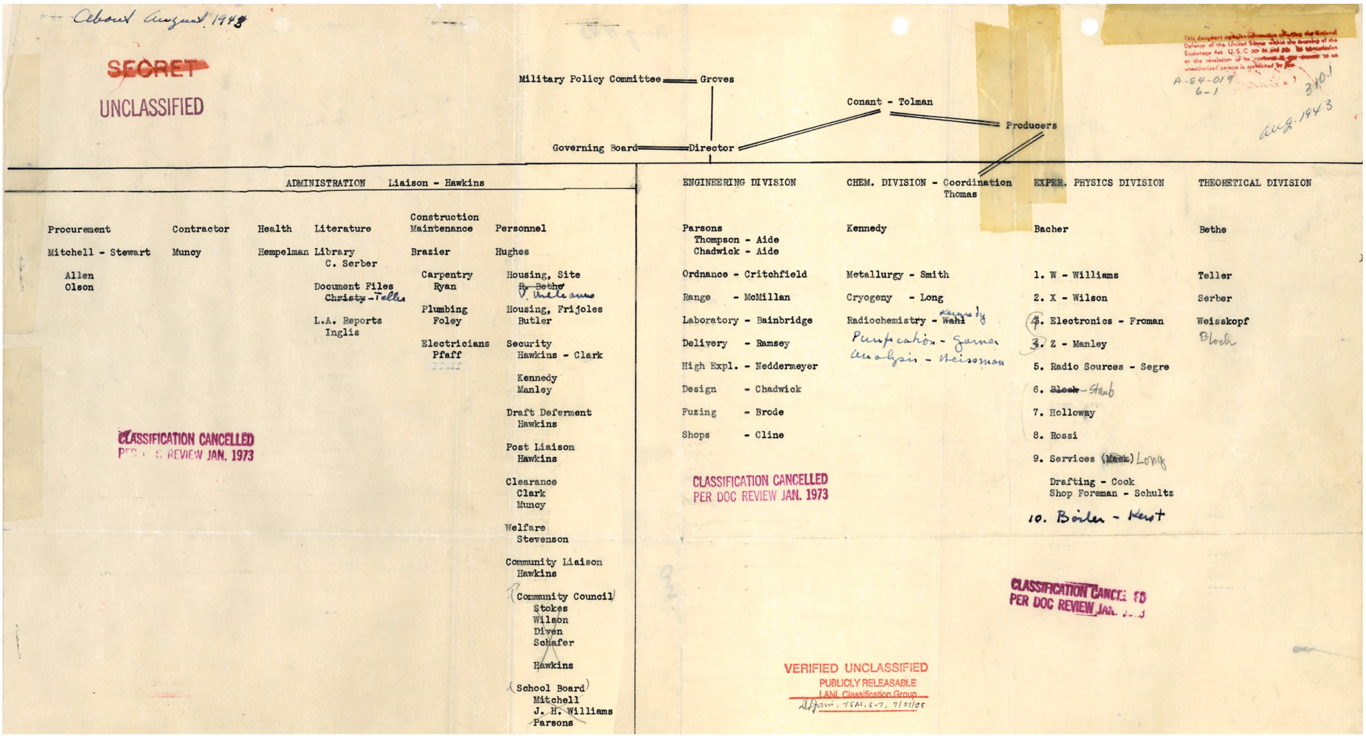


Fig. 4. The Manhattan Project organizational chart (from about August 1943). Vannevar Bush was a member of the Governing Board listed in the top centre of the chart [33].

other government agencies. For example, Bush wrote a letter dated November 14, 1952 to Arthur Goldschmidt, Director of Coordination and Planning, Technical Assistance Administration at the United Nations. In this letter, Bush explains the source of Carnegie Institution's interest in algal research stating, " the interest has come in large part from the realization that the supply of more adequate foods and feeds in many areas of the world could have an important bearing, perhaps decisive, on the feasibility of establishing and maintaining generally amicable international relationships." [Appendix A: Correspondence 1952: H] He also notes the prohibitive costs of mass algal production in the United States but that with "the lower costs of labor and materials in Japan coupled with the ingenuity of the Japanese, the affair seems worthy of vigorous exploration and findings of value could be expected within a period of a few years." [Appendix A: Correspondence 1952: H] The eventual collaboration with Tamiya proved Bush's prediction was correct.

2.2.2. *Hiroshi Tamiya [田宮博] (1903–1984)*

Hiroshi Tamiya was a plant biochemist and microbiologist notable for his research on photosynthesis and the mass culturing of algae. He enrolled in the undergraduate program in microbiology at the Botanical Institute of Tokyo Imperial University in 1923. He came under the influence of the acclaimed Japanese plant physiologist Keita Shibata (1877–1949), who introduced chemistry into botany in Japan, and Hirotarō Hattori (1875–1965), a lecturer of bacteriology. Tamiya remained at the Botanical Institute to work on his doctorate. After graduating in 1926, Tamiya became a member of the Tokugawa Institute on the recommendation of both Shibata and Hattori [30,34]. Hattori had been appointed its director three years earlier. The Tokugawa Institute provided Tamiya with a well-equipped and well-funded laboratory in which to conduct his research. Tamiya was eventually appointed its director in 1946, a position he held until it closed in 1970.

During his long career, Tamiya worked in Japan, Europe and the US. His extensive bibliography includes publications in Japanese, English and German. He was influenced by many leading international scientists [30,34]. For example, between 1926 and 1933, Tamiya initially focused his studies on the changes in pH in the culture medium while growing *Aspergillus*. An influx of German and British scientific papers on cell physiology and biochemistry influenced Tamiya to research respiratory physiology and cytochromes. By 1941, Tamiya, having read about Warburg's research into photosynthesis, started his *Chlorella* studies. He focused on measuring photosynthesis under intermittent light to understand what was happening during the "dark" period [35]. He published a significant article in 1949 with Hiroshi Huzisige based on their eight years' research [36]. It reported the inhibition of photosynthetic productivity by oxygen at high light intensity providing evidence for a Rubisco-type reaction involving carbon dioxide and oxygen fixation.

Tamiya's research with *Chlorella* continued. He turned his attention to the mass culture of algae from 1951 when establishing collaborations with the US. After many trials and errors, Tamiya developed a new culture unit that used an open circulation system with a device for intermittent stirring. Masaaki Honda, a credible observer, described this system when he visited the Tokugawa Institute around 1955: "The building was old and on the entrance was a big board on which was printed 'Tokugawa Biological Institute'. In front of the building was a square, man-made pond with a queer fan twirling water in the middle. The water was green and not transparent. When I rang the bell, Mr. Tokugawa himself came out and, seeing me looking at the pond, smiled and said, 'That's *Chlorella*. Our Institute is studying it to see if we can make food from it.'" [37] Significantly, factories in Japan and Taiwan used this design until the 1980s [34].

2.2.3. *How Bush and Tamiya started the collaborations*

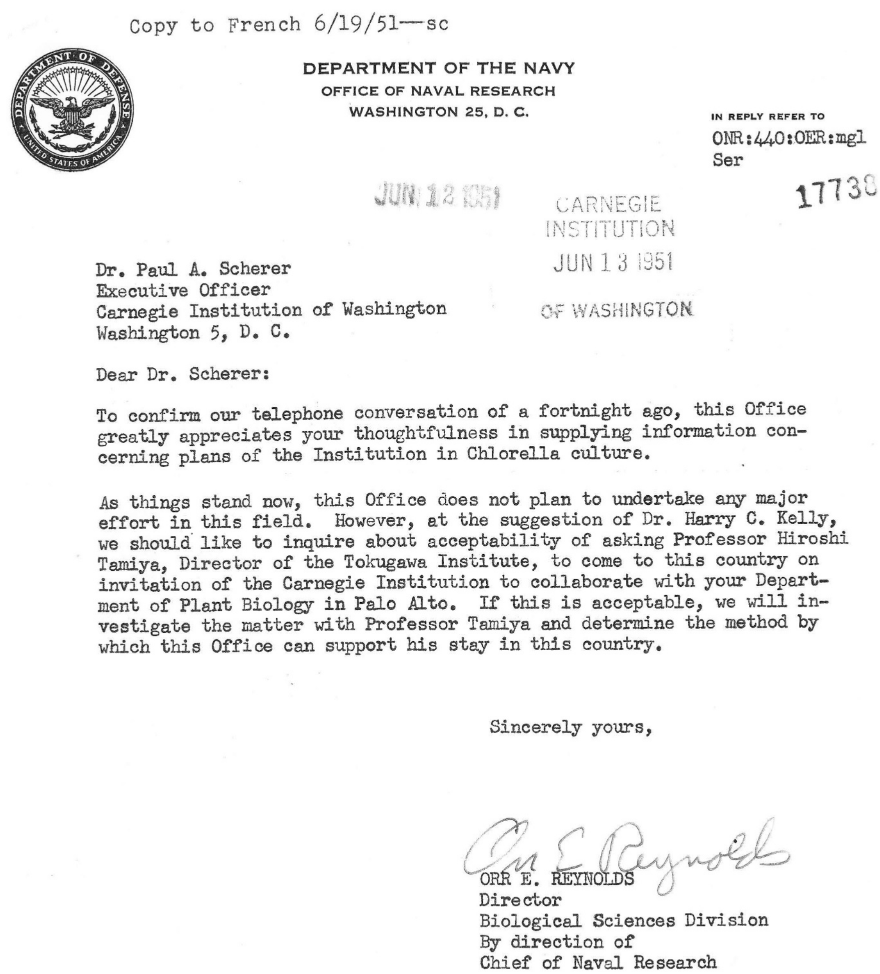
In 1944 President Roosevelt asked Bush to suggest future peacetime applications of technologies developed in World War II. Bush recognized that fuel and food security was a major post-war priority. Tamiya was known to the US government for his liaison between Japanese-American scientists in the immediate post-war years. He was by then a lead microbiologist in Japan and studying *Chlorella*. Under Bush's leadership, Tamiya was invited to visit the US. As part of this process, Orr E.

Reynolds, Director of the Biological Sciences Division of the Office of Naval Research, wrote to Paul Scherer, Executive Officer of the Carnegie Institution, on June 12, 1951, asking about the acceptability of sending an invitation to Tamiya to visit the US to undertake research at the Carnegie Institution of Washington's Department of Plant Biology and to share his knowledge on *Chlorella* culture with US scientists (Fig. 5). [Appendix A: Correspondence 1951: A]

The invitation was extraordinary in the context of the times. Bush had been instrumental in the development of the nuclear bombs that had been dropped on Japanese cities. Bush now proposed that the Carnegie Institution engaged in scientific collaboration with a Japanese scientist when many still regarded the Japanese as "the enemy". Notably, in June 1951, when the Office of Naval Research letter was written, Japan was still under occupation by the US and British, including Australian forces led by the Supreme Commander of the Allied Powers, General Douglas MacArthur [38]. Travel by Japanese citizens to the US was also still mostly by boat and obtaining entry permits was also very difficult. Even before arriving in the US in October 1952, Tamiya was in close contact with researchers at the Carnegie Institution. For example, in April 1951, Tamiya was asked by Harry Spoehr of the Carnegie Institution to assist with a feasibility study of the mass culturing *Chlorella* to be undertaken at the Tokugawa Institute with the aim of it as food for both animals and humans [30]. [Appendix A: Reports 1952: May 19] He was also in contact with other scientists during the rest of 1951, particularly Stacy French, giving progress reports and asking for assistance and information regarding the building of pilot plants. [Appendix A: Correspondence 1951: B]

Bush and Tamiya were also corresponding although direct contact between American and Japanese civilians was still discouraged. On November 28, 1951, Bush wrote to Tamiya [Appendix A: Correspondence 1951 H] explaining that the invitation would be issued soon and that he "will be made most welcome … by Dr. French and his staff." Significantly, a letter by John Burlew, the editor of the monograph, to Stacy French five months earlier on June 19 [Appendix A: Correspondence 1951: C] had stated that Tamiya should only be received if his presence was to be beneficial to the department's work – they should not be there to teach Tamiya. Rather, he was there to teach them! Bush's November letter also outlined the work they had been doing into algal culture, highlighting the work at the Arthur D. Little pilot plant in Cambridge, Massachusetts. He wrote that, as a result of the plant's closure due to winter, "we are going to summarize our work in the field of algal culture by publishing a monograph of about 200 pages. In addition to reports of the work carried out under our auspices, we plan to include contributions from other workers in this field so that the monograph will be a comprehensive survey of present-day knowledge of algal culture. … You and your associates have been very active in algal culture also, according to Dr. French. An account of your experiments would seem to be a worthwhile addition to our monograph. … We would be very happy to have you join us in this monograph, and I hope you will find it possible to accept our invitation." Tamiya accepted the invitation and contributed three articles to the monograph [39–41].

Six months later, in May 1952, and coincidentally the month after



Copy to French 6/19/51—sc

DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH
WASHINGTON 25, D. C.

IN REPLY REFER TO
ONR:440:OER:mgl
Ser 17730

JUN 12 1951

CARNEGIE INSTITUTION JUN 13 1951 OF WASHINGTON

Dr. Paul A. Scherer
Executive Officer
Carnegie Institution of Washington
Washington 5, D. C.

Dear Dr. Scherer:

To confirm our telephone conversation of a fortnight ago, this Office greatly appreciates your thoughtfulness in supplying information concerning plans of the Institution in Chlorella culture.

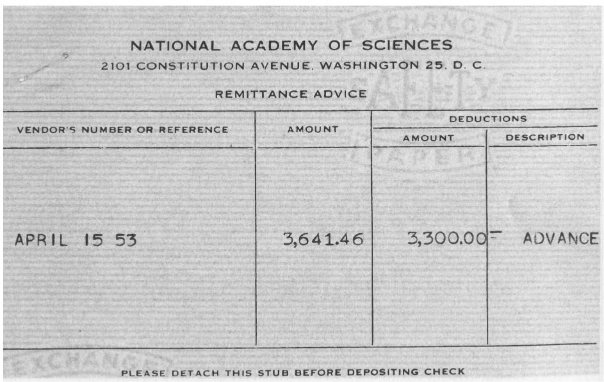
As things stand now, this Office does not plan to undertake any major effort in this field. However, at the suggestion of Dr. Harry C. Kelly, we should like to inquire about acceptability of asking Professor Hiroshi Tamiya, Director of the Tokugawa Institute, to come to this country on invitation of the Carnegie Institution to collaborate with your Department of Plant Biology in Palo Alto. If this is acceptable, we will investigate the matter with Professor Tamiya and determine the method by which this Office can support his stay in this country.

Sincerely yours,

Orr E. Reynolds

ORR E. REYNOLDS
Director
Biological Sciences Division
By direction of
Chief of Naval Research

Fig. 5. A letter dated June 12, 1951 from Orr E. Reynolds, Director of the Biological Sciences Division written by the Office of Naval Research to Paul Scherer, Executive Officer of the Carnegie Institution regarding the acceptability of sending an invitation to Tamiya to visit the US and collaborate with scientists at the Carnegie Institution's Department of Plant Biology.

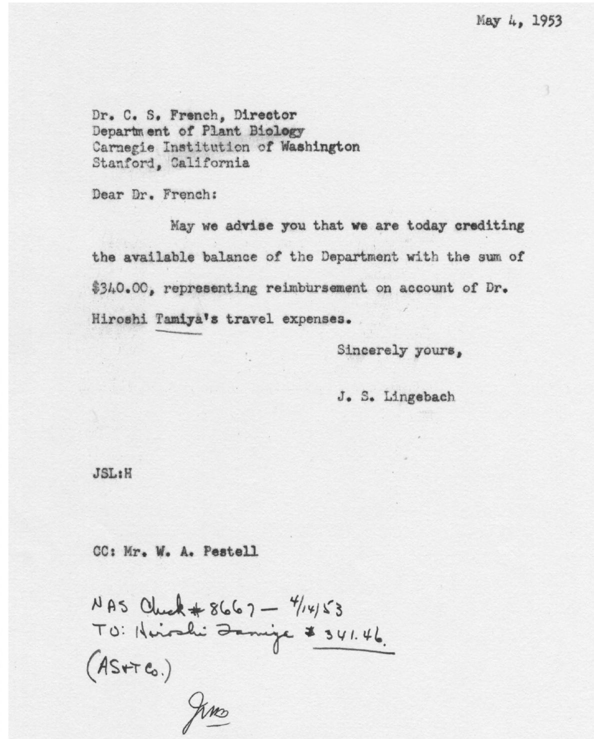


NATIONAL ACADEMY OF SCIENCES
2101 CONSTITUTION AVENUE. WASHINGTON 25. D. C.
REMITTANCE ADVICE

VENDOR'S NUMBER OR REFERENCE	AMOUNT	DEDUCTIONS AMOUNT	DEDUCTIONS DESCRIPTION
APRIL 15 53	3,641.46	3,300.00	ADVANCE

PLEASE DETACH THIS STUB BEFORE DEPOSITING CHECK

a



May 4, 1953

Dr. C. S. French, Director
Department of Plant Biology
Carnegie Institution of Washington
Stanford, California

Dear Dr. French:

May we advise you that we are today crediting the available balance of the Department with the sum of $340.00, representing reimbursement on account of Dr. Hiroshi Tamiya's travel expenses.

Sincerely yours,

J. S. Lingebach

JSL:H

CC: Mr. W. A. Pestell

NAS Check #8667 — 4/14/53
TO: Hiroshi Tamiya $341.46
(AS+T Co.)

b

Fig. 6. Documents from the Carnegie Institution archives show (a) The check details for the payment of research costs during Tamiya's stay were paid to the Carnegie Institution's Department of Plant Biology at the end of his stay in the US. (b) A letter advising that Tamiya's travel expenses had been reimbursed to the Department of Plant Biology on May 4, 1953 after he had left the US to return to Japan.

the enactment of The San Francisco Treaty that officially ended the war, Tamiya sent a report to the Carnegie Institution from Japan. It provided details of the search for suitable algal strain and culture conditions, the outdoor mass culture of *Chlorella*, the kinetic analysis of the growth of algae and attempts by scientists at the Tokugawa Institute to process algae for human consumption. [Appendix A: Reports 1952: May 19]

In October 1952, Tamiya finally arrived in the US and was able to meet Bush. After the first meeting with Bush, Tamiya wrote that he was "deeply impressed by his [Bush's] erudition and personality which was reminiscent of our Samurai." [p. 5, 30] Tamiya stayed in the US for approximately six months. He worked at the Carnegie institution's Department of Plant Biology undertaking lab work and report writing. [Appendix A: Correspondence 1952: C] The visit was supported by a Fellowship funded by the Office of Naval Research. Documents held in the Carnegie Institution confirm that Tamiya's travel expenses and research costs were reimbursed (Fig. 6). [Appendix A: Correspondence 1953: N]

3. Major outcomes from the US-Japan collaborations in algal research in the 1950s

The collaborations between the US and Japan delivered a range of outcomes in the early 1950s. This section presents an overview of the major outcomes based on the monograph and selected primary documents. Supplementary material documents provide more details.

3.1. Algal Mass Culture Symposium (1952) held at Stanford University

At the beginning of Tamiya's first visit to the US in 1952, the Carnegie Institution organized the Algal Mass Culture Symposium at Stanford University. As noted previously, it brought together leading US scientists and those from Japan, including Tamiya and other countries. The monograph's publication associated with this event, Algal Culture: From Laboratory to Pilot Plant, has been noted. It captured the accumulated knowledge on algae, particularly *Chlorella*, from as early as the 1890s from the US, Europe, Israel and Japan. Further details are relevant. It systematically presents the current state of algal research in 1952 in the US and, more generally, the world. It aimed to aid anyone interested in cultivating algae and provide a blueprint for those who wanted to set up pilot plans. The editor, John Burlew, was not an expert on algae or biofuels, but had had a distinguished career in other fields. He was awarded the Presidential Medal of Merit in 1948 for his work with the National Defence Research Committee and knew Bush from that Committee. Burlew's primary role was as editor of the collection of articles, but he also contributed to the introduction, the conclusion and one article on the nutritional value of microalgae [42].

Most of the authors in the monograph were scientists in the Department of Plant Biology of the Carnegie Institution of Washington and other American institutions and industries, such as the University of Texas and Merck and Company Inc. There were also articles by other leading scientists, including Bessel Kok from the Agricultural University of Wageningen in Holland, Hans von Witsch and Richard Harder from Göttingen University in Germany, Dorothy M. Collyer and G. E. Fogg from University College, London and M. J. Geoghegan from Imperial Chemical Industries Ltd. in the UK, Jorgen Jorgenson and Jacinto Convit from Venezuela, M. Evenari, A. M. Mayer and E. Gottesman from the Hebrew University in Israel, and Tamiya and his colleagues from the Tokugawa Institute.

The twenty-two articles are divided into five parts. Part I introduces the reader to the current state of mass culturing algae and its possible use as a new food source instead of photosynthetically inefficient higher plants. Part II focuses on the conditions for algal growth, covering the basic biology of algae, the growth characteristics when mass cultured, the efficiency of the photosynthesis, what sort of illumination has the most beneficial effect and the best culture, that is, the chemical environment, in which to grow algae. Part III investigates the growth of algae in mass culture, in other words, the different methods of growing algae, and *Chlorella* in particular, and the results these methods produced. This section encompasses the first laboratory experiments on *Chlorella* culture at the Department of Plant Biology, how Chlorella grows in non-sterile cultures, in greenhouses, the open air and how its growth is affected by freshwater microorganisms in the tropics, the simplest and cheapest method of growing algae that would also save water, how the growth of *Chlorella* is dependent on light and temperature, and the quantity of lipids produced by algae and how that differs between species. Part IV examines the pre-pilot-plant experiments conducted by Hiroshi Tamiya at the Tokugawa Institute and the pilot-plant experiment carried out by Arthur D Little Inc. in Cambridge, Massachusetts. Finally, Part V considers the possible uses for algae depending on its chemical composition. It includes a discussion of algae as a food source for humans and animals, as a raw material for industry and as a tool for medical research. The extensive bibliography points to research into the mass culture of *Chlorella* and related subjects between 1900 and 1952 from the US, Japan, Germany and Britain.

In the monograph's Foreword (p. iv) [1], Bush noted: "By no means all problems involved in algal culture have been obtained, but partial answers to the principal questions have been obtained. The alga *Chlorella* has been grown and harvested continuously on a large scale… and estimates have been made as to possible yields of Chlorella in commercial quantities, based on the best data at present available."

More recent comments on the monograph by algal researchers confirm its relevance to the field more than 50 years later. M. Borowitzka noted, "If you want to run an outdoor microalgae facility, just pick up the Burlew monograph and run with it. It is not out of date, and it is every bit as important now as then." (Personal communication, Melbourne, Australia, 2007.) More recently, J. Weissman commented, "The Burlew monograph was indeed fundamental to research at the Aquatic Species Program and constantly used by the researchers there." (Personal communication, Boulder, Colorado, 2019).

Table 1 compares research themes covered in the Algal Symposium in 1952 with the Algal Biomass, Biofuels and Bioproducts Conference (hereafter Algal BBB) in 2021 and the *Algal Research* journal in 2021 [42]. It confirms the relevance of the earlier research to work today. It also shows that there is a strong correlation between the different sources. The main difference is seen in new technological developments associated with algal genetics research, reported at Algal BBB or in *Algal Research* presented on its website in June 2021 [43].

3.2. Tamiya visits US research institutions (1952–1953)

During his six months in the US between October 1952 and April 1953, Tamiya visited institutions and industries across the US to meet with 77 scientists to discuss the problems of photosynthesis and algal mass culture. [Appendix B1] Many of these organizations still have active algal programs and continue to be represented in Algal BBB conferences. For example, Tamiya visited national laboratories, Scripps Institution of Oceanography, the University of Texas-Austin, the California Institute of Technology, and corporations such as Arthur D. Little Inc. in Cambridge, Massachusetts and Dow Chemical Co. Tamiya was finally able to finish carbon dioxide and oxygen fixation experiments interrupted by the war in the cyclotron at the Berkeley Radiation Laboratory [30].

3.3. Tamiya visits five countries on his return journey to Japan from the US

Tamiya left the US in April 1953. On his way back to Japan, he visited five countries (Britain, France, Netherlands, Germany and Israel) and met with 27 scientists. [Appendix B2] These countries also continue to have active algal research programs. He wrote a three-page letter dated June 30, 1953 to report to Vannevar Bush and Peter Sherer (Executive Officer at the Carnegie Institution) regarding his discussions with "almost all organizations and scientists related to the problem of algal culture" in Europe and Israel. [Appendix A: Correspondence 1953: O] It included hand-drawn sketches of an algal pond design. (Fig. 7 presents an excerpt of the letter. The full text is available in Appendix C.) The report was well-received, Stacy French writing to Paul Scherer, the Executive Officer of the Carnegie Institution, regarding the receipt of an "excellent letter" on Tamiya's visits to algal projects on his return journey. [Appendix A: Correspondence 1953: Q]

By the time Tamiya arrived home in Japan, the Symposium monograph had just been published. Paul Scherer, Executive Officer of the Carnegie Institution, writing to Tamiya, informed him that they would be sending copies soon. [Appendix A: Correspondence 1953: R] These duly arrived in September and Tamiya subsequently received permission to reprint three chapters in Studies of the Tokugawa Institute. [Appendix A: Correspondence 1953: S]

3.4. Tamiya and Chlorella for food

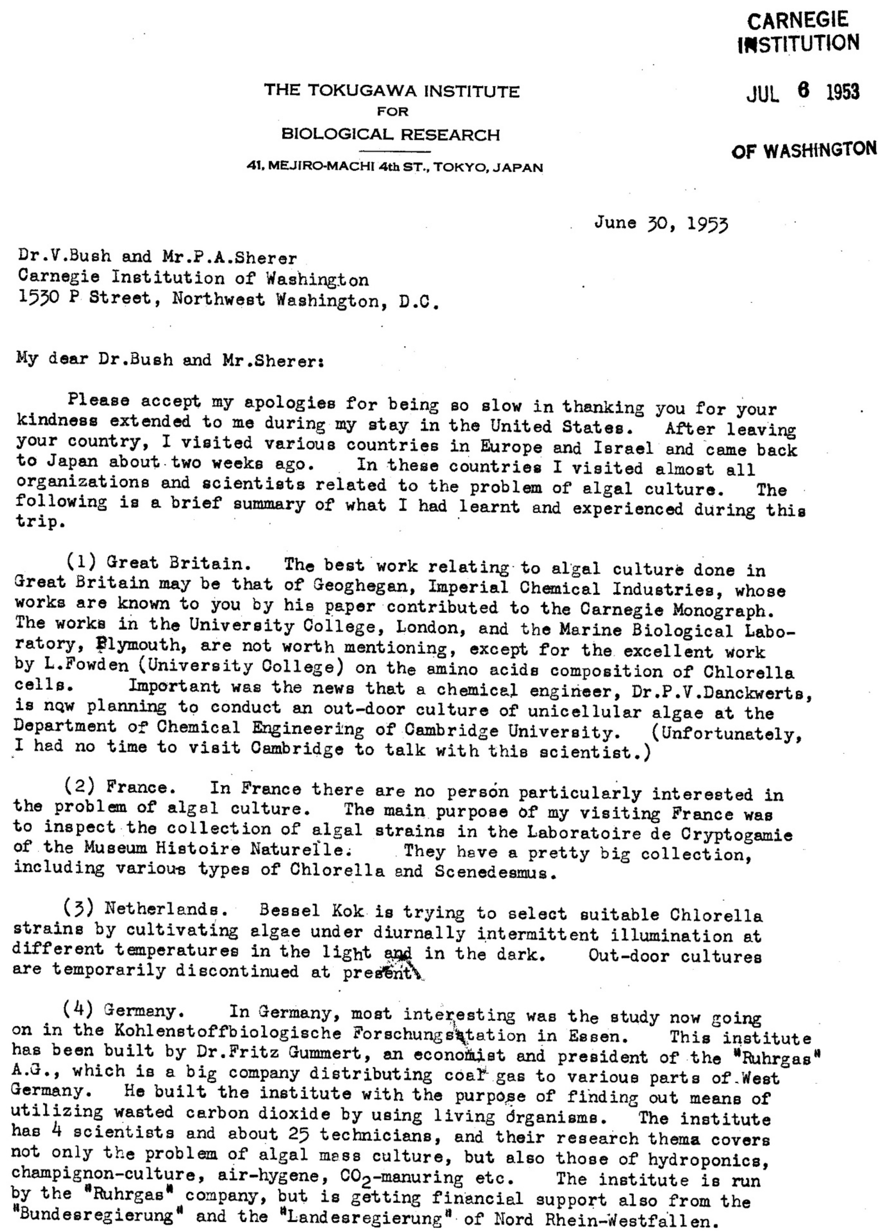
In his Foreword to the monograph, Bush remarked on the potential of large-scale culture of algae as a source of high-protein food. After the war, there were food shortages across Europe, North America and Japan. In 1946 the first World Food Survey concluded that a third of the world's population would not be receiving sufficient nutrients [44].

An unexpected discovery in this study by the author was that Tamiya became associated with the US Mutual Security Program (MSP) plans to build a pilot commercial-size algal production plant near Taipei in the Formosa [Taiwan] FY 1954 program (Fig. 8). [Appendix A: Reports 1953: B]

The US Congress had passed the Mutual Security Act in October 1951. The MSP mission was "to organize military, economic, and technical assistance to friendly countries to strengthen the mutual security …, to develop their resources…and to facilitate the effective participation of those countries in the United Nations…" [45]. It covered a broad geographic area including Europe, Asia and the Pacific. Part of this brief

Table 1
A comparison of research themes at the Algal Symposium in 1952 [1], at the Algal Biomass, Biofuels and Bioproducts Conference in 2021 and on the *Algal Research* website in June 2021 [43].

Algal Symposium 1952 (based on Burlew 1953 [1])	*Algal Research* 2021 (journals.elsevier.com/algal-research)	Algal BBB 2021 (recent developments in bold)
Algal Biology	Algal Biology	Algal Biology (molecular engineering and synthetic biology)
Algal Cultivation	Algal Cultivation	Algal Biotech (metabolic regulation)
Algal Co-Products	Algal Products	Algal Cultivation
Algal Harvesting	Algal Harvesting/Extraction	Algal Bioproducts (including high value products and co-products)
Growth of Algae in Mass Culture	Algal Biomass	Algal Harvesting and Extraction Systems
Economic Appraisal	TEA/LCA Sustainability Assessments/Analysis	TEA/LCA, Sustainability, Modeling/Analysis
Engineering Approaches	Biorefinery Assessments and Analyses	Engineering/Control
		Engineering Technologies, Engineering of Biorefinery systems. Bioreactor Design
New Technologies		New Technologies



CARNEGIE
INSTITUTION
JUL 6 1953
OF WASHINGTON

THE TOKUGAWA INSTITUTE
FOR
BIOLOGICAL RESEARCH
41, MEJIRO-MACHI 4th ST., TOKYO, JAPAN

June 30, 1953

Dr.V.Bush and Mr.P.A.Sherer
Carnegie Institution of Washington
1530 P Street, Northwest Washington, D.C.

My dear Dr.Bush and Mr.Sherer:

Please accept my apologies for being so slow in thanking you for your kindness extended to me during my stay in the United States. After leaving your country, I visited various countries in Europe and Israel and came back to Japan about two weeks ago. In these countries I visited almost all organizations and scientists related to the problem of algal culture. The following is a brief summary of what I had learnt and experienced during this trip.

(1) Great Britain. The best work relating to algal culture done in Great Britain may be that of Geoghegan, Imperial Chemical Industries, whose works are known to you by his paper contributed to the Carnegie Monograph. The works in the University College, London, and the Marine Biological Laboratory, Plymouth, are not worth mentioning, except for the excellent work by L.Fowden (University College) on the amino acids composition of Chlorella cells. Important was the news that a chemical engineer, Dr.P.V.Danckwerts, is now planning to conduct an out-door culture of unicellular algae at the Department of Chemical Engineering of Cambridge University. (Unfortunately, I had no time to visit Cambridge to talk with this scientist.)

(2) France. In France there are no person particularly interested in the problem of algal culture. The main purpose of my visiting France was to inspect the collection of algal strains in the Laboratoire de Cryptogamie of the Museum Histoire Naturelle. They have a pretty big collection, including various types of Chlorella and Scenedesmus.

(3) Netherlands. Bessel Kok is trying to select suitable Chlorella strains by cultivating algae under diurnally intermittent illumination at different temperatures in the light and in the dark. Out-door cultures are temporarily discontinued at present.

(4) Germany. In Germany, most interesting was the study now going on in the Kohlenstoffbiologische Forschungsstation in Essen. This institute has been built by Dr.Fritz Gummert, an economist and president of the "Ruhrgas" A.G., which is a big company distributing coal gas to various parts of West Germany. He built the institute with the purpose of finding out means of utilizing wasted carbon dioxide by using living organisms. The institute has 4 scientists and about 25 technicians, and their research thema covers not only the problem of algal mass culture, but also those of hydroponics, champignon-culture, air-hygene, CO_2-manuring etc. The institute is run by the "Ruhrgas" company, but is getting financial support also from the "Bundesregierung" and the "Landesregierung" of Nord Rhein-Westfallen.

Fig. 7. An excerpt from a letter written by Tamiya in June 1953 to the Carnegie Institution on his discussions with scientists and observations of algal projects in Britain, France, Netherlands, Israel and Germany during his return visit to Japan between April and June 1953.

included technical assistance to ensure food security in places like Taiwan. The status of Taiwan (formerly Formosa) in 1953 was quite different. Tamiya's involvement is therefore not as unlikely as it first appears.

The 19-page report dated May 25, 1953 from the MSA in Washington to the MSA Mission in Taipei notes Tamiya's recent success in the mass culture of algae. It suggests the consideration of "a pilot commercial size project for the manufacture of *Chlorella*." [Appendix A: Reports 1953: B] It discusses preliminary experiments undertaken at the Tokugawa Institute in collaboration with the Carnegie Institution on *Chlorella* as a source of human food. It provides results for the nutrient value of Chlorella that were subsequently published in 1954 [46]. It also includes recipes created by Nobuko Tamiya, the wife of Hiroshi Tamiya, using *Chlorella* as an ingredient for cookies, bread rolls and ice cream (Fig. 9). She had completed a Cordon Bleu diploma in Paris in 1934 and contributed to the experimental work. Given that green tea ice cream is still ubiquitous in Japanese restaurants, it is not surprising that the Japanese thought *Chlorella* ice cream was palatable.

The Mutual Security Program was dissolved three months after the report (and the Department of [Atomic] Energy was established a few months later in 1954). The Taipei plant was therefore not built at that time. However, as noted, Tamiya's design for an algal production plant developed at the Tokugawa Institute became the basis for commercial plants in Taiwan that operated from the 1960s until the 1980s.

3.5. Mass culture of algae

By 1954 Tamiya's status in the US was very high for his significant developments with the mass culture of algae and pilot program. A letter from Stacy French to another staff member at the Carnegie Institution in Washington dated March 10, 1954 states: "The only progress in mass culture [of algae] has been by Tamiya." (Fig. 10). [Appendix A: Correspondence 1954: B]

Tamiya was involved in many algal studies at the Tokugawa Institute between 1924 and 1970 (when it was shut down). The ten volumes of the publications from this period are difficult to obtain. The author

)ESPATCH CONTINUATION — MUTUAL SECURITY AGENCY

SECURITY CLASSIFICATION: UNCLASSIFIED — DESPATCH NO. TOMUS D-35

POST: MSA TAIPEI — PAGE 2 OF 14 PAG

MUTUAL SECURITY AGENCY
Washington 25, D. C.

AD/FE-CI-221 May 25, 1953

Honorable Hubert G. Schenck
Chief, MSA Mission to China
Taipei, Taiwan

Dear Hu:

Dr. Vannevar Bush, President of the Carnegie Institution of Washington and top advisor to the Government on the atomic bomb development and other scientific advances, has brought to our attention a method of producing an algae, "chlorella", which contains a high percentage of protein fit for feed and food, with the suggestion that we consider including a pilot commercial-size project for the "manufacture" of chlorella in our Formosa FY 1954 program.

Fig. 8. An excerpt of the report dated August 3, 1953 from the Mutual Security Agency office in Washington to the Mutual Security Agency Mission in Taipei regarding building a pilot commercial-size algal production plant near Taipei in 1954.

:SPATCH NTINUATION — MUTUAL SECURITY AGENCY

SECURITY CLASSIFICATION: UNCLASSIFIED — DESPATCH NO: TOMUS D-35

MSA TAIPEI — PAGE 8 OF 14 PAGES

Richer in taste were rolls prepared with the following materials: 8 tablespoons (56 g) of Chlorella powder, 4 cups (568 g) flour, ½ cup (110 g) butter, 1 cup (237 ml) milk, 7 tablespoons (99 g) sugar, 2eggs, 1 teaspoon (13 g) salt, and one yeast cake. Addition of nuts increased the attractiveness of the rolls in taste, texture, and appearance. Fancy-looking rolls with variegated colors were prepared by laye·ing ordinary dough alternately with that containing Chlorella.

(5) Cookies. Different kinds of green-colored cookies were prepared by mixing Chlorella powder with flour. Appropriate proportions of ingredients for a simple recipe are: 2 teaspoons (4.7 g) Chlorella powder. 2 cups (226 g) cake flour, ½ cup (114 g) sugar, ¼ lb butter, and 1 small egg.

(6) Ice cream/ Surprisingly large amounts of Chlorella powder can be added to ice creams. Not only is the dark green color of the algae diluted to a pleasant light green, but also the characteristic taste of the algae effectively accentuates the basic taste of ice cream. To one cup of vanilla ice cream, more than 5 teaspoons Chlorella powder may be added. The proportionof ingredients in such an ice cream is, for example, as follows: 10 tablespoons (71 g) Chlorella powder, 4 cups evaporated milk(1000 g), 2 cups (473 ml) milk, 1 tablespoon (89 g) flour, 1 c. (227 g) sugar, 2eggs (98 g), and 2 tablespoons(30 ml) vanilla extract.

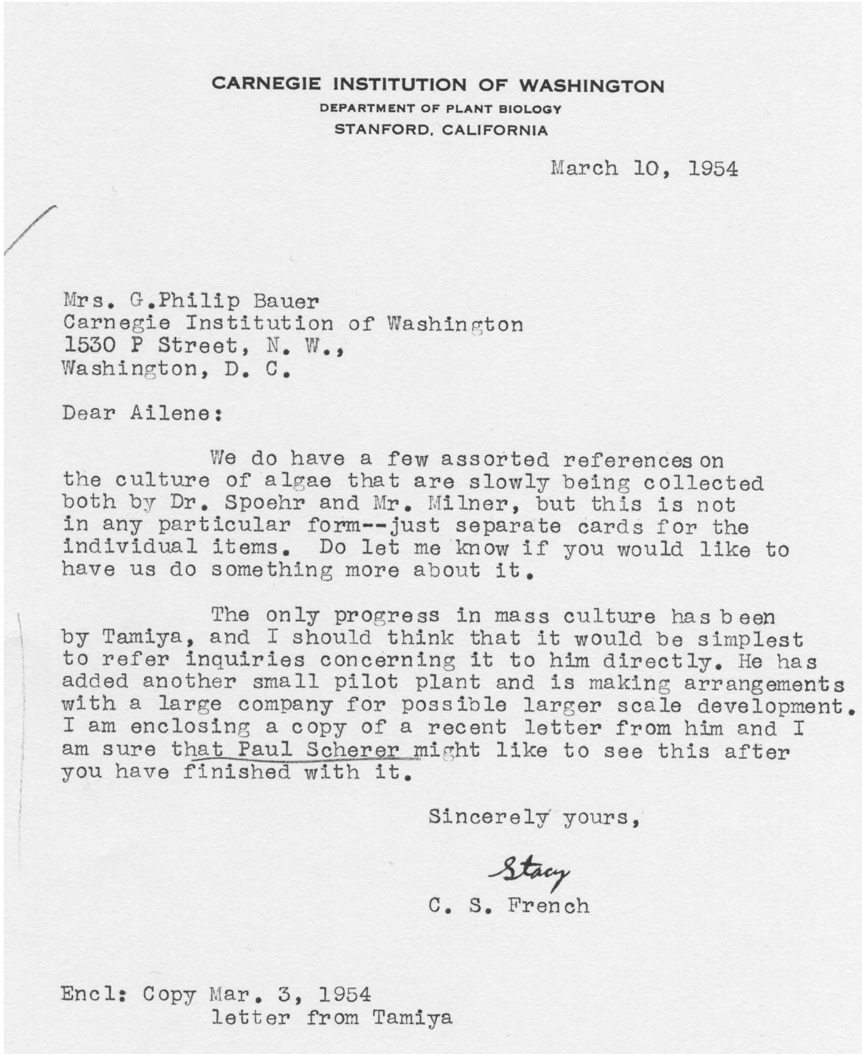
Fig. 9. Recipes for bread rolls, cookies and ice cream using *Chlorella* powder created by Mrs. Tamiya were included in the 1953 Mutual Security Agency report from the Washington office to the Taiwan mission.

tracked one set to a US professor. He denied access and after his death, records of their location were lost. The author subsequently found a complete set in the Special Collections archive at the University of Melbourne in Australia. These provide insights into algal research in Japan more generally during nearly 50 years of publication, but information on studies of the use of algae for fuel is still limited. However, unpublished research reports by Tamiya on progress with his pilot plant and early experimental work for a pilot plant for the mass culture of *Chlorella* were sent to the Carnegie Institution. [Appendix A: Reports: 1952–1954] For example, Fig. 11 is a copy of a photograph of Tamiya's pilot plant in Tokyo sent to the Carnegie Institution in 1952. [Appendix A: Miscellaneous] The reports provide insights into his research and the development of the mass culture of algae in Japan.

Tamiya later published this research in articles, notably 'The mass culture of algae' in the *Annual Review of Plant Physiology* in 1957 [47]. It is still available. It is the culmination of Tamiya's research pathway to that date. A Rockefeller Foundation Grant of $25,000 supported the research for five years between 1954 and 1959. Tamiya also received a donation of plastic sheeting that was hard to obtain in post-war US and unavailable in Japan. The references and other correspondence associated with this publication confirm that collaborations between American and Japanese scientists continued in the 1950s.

Tamiya describes his culture techniques in the 1957 article. However, we need to turn to his monograph article [41] from 1953 to obtain further details. Fig. 11, as mentioned, provides a general view of the pilot plant from 1952 as an open circulation system. It has a shallow pond as a growth unit consisting of a concrete trough with plastic covers for climate and animal control. There are no paddle wheels although these were subsequently added, as noted previously (Section 3.4). The second component is the control house. The third component is a gas exchange tower. Tamiya and his colleagues used the gas exchange tower to enrich the culture medium by bubbling carbon dioxide through the algal suspension. The carbon dioxide was made mainly from burning gas passed through a compressor because compressed gas was unavailable.

The article reports on a diverse range of experiments in Tokyo at the Tokugawa Institute. For example, the productivity from the indoor cultivation of *Chlorella* was investigated with different methods and the best results were obtained from turbulent culture. Outdoor



CARNEGIE INSTITUTION OF WASHINGTON
DEPARTMENT OF PLANT BIOLOGY
STANFORD, CALIFORNIA

March 10, 1954

Mrs. G.Philip Bauer
Carnegie Institution of Washington
1530 P Street, N. W.,
Washington, D. C.

Dear Ailene:

We do have a few assorted references on the culture of algae that are slowly being collected both by Dr. Spoehr and Mr. Milner, but this is not in any particular form--just separate cards for the individual items. Do let me know if you would like to have us do something more about it.

The only progress in mass culture has been by Tamiya, and I should think that it would be simplest to refer inquiries concerning it to him directly. He has added another small pilot plant and is making arrangements with a large company for possible larger scale development. I am enclosing a copy of a recent letter from him and I am sure that Paul Scherer might like to see this after you have finished with it.

Sincerely yours,

Stacy

C. S. French

Encl: Copy Mar. 3, 1954
letter from Tamiya

Fig. 10. A letter dated March 10, 1954 from Stacy French to another staff member at the Carnegie Institution regarding Tamiya's progress in the mass culture of algae.

productivities for *Chlorella* and Scenedesmus were also investigated. Seasonal outdoor growth for mesophilic and thermophilic Chlorella strains productivities is also reported with up to 17.6 g/m^2/day reached for *Chlorella ellipsoidea* (a mesophilic *Chlorella*). Outdoor cultivation results for continuous culture in Tokyo in 1956, also for *Chlorella ellipsoidea,* show an annual average of 12.1 g/m^2/day. Importantly, Tamiya noted that a process plant located in a more favorable climate than Tokyo with more sunshine should produce an average of 20 g/m^2/day.

Table 2 compares the algal productivities reported in Tamiya's 1957 article [47] with those listed in the State of Technology Reports (2015–2020) for research conducted under the Bioenergy Technologies Office of the US Department of Energy [48]. It shows that Tamiya's results of 12.1 g/m^2/day were achieved as recently as 2018 in Arizona. Higher averages of 20 g/m^2/day and more were also recently obtained in the Arizona summer. These results highlight how vital sunshine and summer productivities are to the overall results.

Tamiya's article also reports on results in other familiar areas for algal research. For example, Tamiya and colleagues decided after much trial and error that the pond depths should be 5 to 20 cm. They also conducted a range of experiments to determine the ash free dry weight and measured up to 55 g/l. However, they concluded that 1 to 2 g/l was more realistic. They also had serious problems with contamination by protozoa and rotifers. They discovered they could eliminate the contaminants without affecting the algae by using very low concentrations of two chemicals 2,4-dinitro-6-cyclohexyl phenylacetate or pentachlorophenyl acetate. Tamiya also investigated the nutritional quality of algae and reported details of early trials that were still in progress.

These results highlight how Tamiya's research reported in the monograph and this review article remains pertinent to current research in algal biomass, biofuels and bioproducts.

4. Perspectives on key developments in early algal biofuels research in the US and Japan

The relative support for algal research in the US and Japan may be glimpsed from a comparison of publications on algae by citation (1900–2014) in the benchmark Aquatic Species Program Closeout Report (1998) [2], the National Algal Biofuels Technology Roadmap (2010) [3] and the National Alliance for Advanced Biofuels and Bio-Products Final Report (2014) [4] [Fig. 12]. It shows that there have been three phases of algal research. The first phase of algal research, frequently overlooked, is highlighted by the box and focuses on the late 1930s to the 1950s. As discussed in this article, the 1950s were an intense period of scientific activity for US algal research, but it became less prominent in the 1960s as oil prices fell. While some photosynthesis research continued, the government diverted funds to higher priorities.

Fig. 11. A photograph of Tamiya's pilot plant in Tokyo in 1952 [46].

Table 2
A comparison of the productivities of algae reported by Tamiya in 1957 [47] and the State of Technology Reports (2015–2020) [48] (Units in g/m^2/day).

	Tamiya 1957	2015 SOT	2016 SOT	2016 SOT	2017 SOT	2018 SOT	2019 SOT	2020 SOT
	(Tokyo)	(Florida/ATP3)	(Florida/ATP3)	(ABY1 performer)	(ASU/ATP3) (Arizona)	(ASU ATP3/ DISCOVR/RACER) (Arizona)	(ASU/DISCOVR) (Arizona)	(ASU/DISCOVR) (Arizona)
	Chlorella sp.	*Nannochloropsis* sp.	*Nannochloropsis* sp. *Desmodesmus* sp.	*Nannochloropsis* sp.	*Nannochloropsis* sp. *Desmodesmus* sp. *Kirchinella* sp. *Scenedesmus* sp.	*Nannochloropsis* sp. *Desmodesmus* sp. *Monoraphidium* sp. *Scenedesmus* sp.	*Nannochloropsis* sp. *Desmodesmus* sp. *Monoraphidium* sp. *Scenedesmus* sp.	*Picochlorum* sp. *Monoraphidium* sp. *Scenedesmus* sp.
Fall	15.0	6.8	7.0	7.8	8.5	8.5	11.4	15.0
Winter	5.6	5.0	5.0	4.8	5.5	7.7	6.5	8.3
Spring	15.8	11.4	11.1	13.0	13.2	15.2	18.7	18.5
Summer	11.8	10.9	13.3	17.5	14.1	15.4	27.1	31.6
Average	12.1	8.5	9.1	10.7	10.3	11.7	15.9	18.4

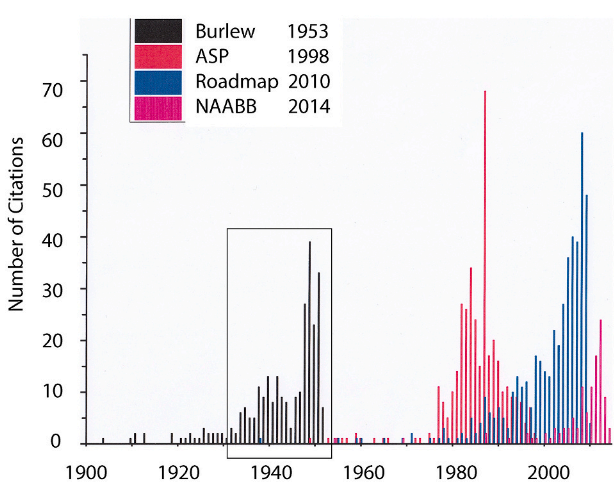


Fig. 12. A comparison of publications on algae by citation (1900–2014) in the Burlew (1953) monograph [1] the Aquatic Species Program Closeout Report (1998) [2], National Algal Biofuels Technology Roadmap (2010) [3] and National Alliance for Advanced Biofuels and Bioproducts Final Report (2014) [4].

The second phase begins in the late 1970s when biofuels research once again gained popularity. In 1978 the U.S. Department of Energy's Office of Fuels Development started to fund the Aquatic Species Program, associated with the biofuels program at the Solar Energy Research Institute (SERI). SERI, as the precursor to National Renewable Energy Laboratory (NREL), was established by President Carter as a direct consequence of the Iranian hostage crisis that began in 1979. It raised fears that the situation may cut off the oil supply from the region and that liquid fuel costs would soar. SERI's primary focus was the production of biodiesel from high lipid-content algae grown in ponds. It was, therefore, necessary for the program's researchers to create a collection of algae that produced not only a lot of oil but could also grow under severe conditions, such as extremes of temperature, pH and salinity. The program eventually developed a collection of approximately 300 species of algae and diatoms from all over the US. The work conducted by the Aquatic Species Program discovered that it was feasible to produce large-scale algal growth in open ponds. Although they reached their targets for the program, they found it was not a monetary cost that hampered the production of biofuel but a biological one: they needed an organism that was more productive in converting sunlight to biomass. When the Aquatic Species Program was shut down in 1996, research into biofuels did continue, but the focus mostly turned to sources other than algae.

We are now in the third phase of modern algal biotechnology. In 2008, a National Algal Biofuels Workshop held at College Park in Maryland resulted in the *National Algal Biofuels Technology Roadmap* [3] published two years later. This roadmap identified problems that needed to be overcome to produce biofuel from algae and be economically feasible. It was not until 2010 that attention returned to algal mass culture research. The National Alliance for Advanced Biofuels and Bioproducts (NAABB) was a consortium of participants from government and non-government laboratories, academia, industry and other entities. It aimed to advance the work of the Aquatic Species Program that had focused on producing enough high-fat content algae to make the production of biofuels possible. NAABB took this work further by selectively cultivating strains of high fat producing algae and then extracting those fats and converting them to fuel and feedstock for animals. In the three years that NAABB operated, they "developed new methods for screening strains to better predict their performance in large-scale open outdoor ponds at any geographical location at any time of the year" [4]. As a result of these biological improvements, the operating costs associated with mass culturing algae for biofuels were reduced.

More recently, the Bioenergy Technologies Office Multi-Year Program Plan (2016) provides an overview of the US goals and structures for algal research, including targets to 2030, that guide and help coordinate its activities [49]. The Algal BBB conferences and the Algal Research journal highlight specific improvements that continue to address the economic viability of biofuels in the US and globally. The development of bioproducts from algae and their current industrial applications are also receiving greater attention [50].

By comparison, a perspective on the developments in Japan is captured by returning to the work of Tamiya and his fellow researchers from the Tokugawa Institute and the Institute of Applied Microbiology at the University of Tokyo. They continued research on the mass culturing of algae. In the late 1950s up until 1965, their research resulted in many publications based on *Chlorella* and other species of algae. Tamiya's contributions were recognized on his 60th birthday when the Japanese Society of Plant Physiology published a special edition of the journal Tamiya had started, *Plant and Cell Physiology* [51,52], with 54 articles from international scholars. It covers a broad range of topics in microalgae and cyanobacteria that had been prominent in Tamiya's research. It includes articles on taxonomy, growth physiology, photosynthesis, enzyme reactions and carbon metabolism, and phosphorous and sulfur metabolism. This special issue should also be acknowledged for the way it provides critical updates from international researchers for work in microalgae and cyanobacteria and the influence of Tamiya for the decade following the Stanford symposium and the Carnegie Institution's monograph under review here. In 1966 Tamiya published a significant article on the synchronous culture of algae [53]. Tamiya's published research subsequently decreased, although, as noted, he remained as Director of the Tokugawa Institute until 1970 when it was closed.

With the closure of the Tokugawa Institute, the Institute of Applied Microbiology continued to publish research on *Chlorella*. However, by the 1990s, following a restructuring, the focus changed to other specializations. Nevertheless, algal research for biofuels and bioproducts continues in Japan. The leading five institutions associated with these developments are the Tokyo University of Agriculture and Technology, the Tokyo Institute of Technology, the University of Tsukuba and the Japan Science and Technology Agency. The fifth institution is the New Energy and Industrial Technology Development Organization (NEDO). It is the government agency that currently leads biofuel research in Japan with its program for the Development of Production Technologies for Biojet Fuels (2017to 2024). Many other universities in Japan, including Hokkaido, Osaka City, Oita and Keio and the National Institute of Advanced Industrial Science, also have active algal research programs that continue to advance the development of algal biofuels. There are also well-established commercial applications of the mass culture of algae, including *Chlorella*. For example, Chlorella Industry Co. Ltd., founded in 1964, manufactures a local species (*Chlorella chikugo*) for a wide range of products [54]. Other companies such as Euglena have successful commercial health care businesses, especially food products and cosmetics [55].

5. Implications for current and future research

This review highlights continuities in the core science of algal research focusing on biofuels in the decades since World War II. The successful mass outdoor culture of algae, particularly *Chlorella*, in Japan in the 1950s had productivities on a par with results reported in the US as recently as 2018. Some lessons have been learned from the early collaborations between the US and Japan. Many have been overlooked, partly due to the tendency of researchers to focus on recent publications that leave earlier vital research hidden from view. Productivity issues such as those concerned with carbon dioxide recognized in the 1950s are, however, now receiving close attention as in the funding of new research projects. New technologies not available in the 1950s such as those for molecular engineering and metabolic regulation are helping to advance knowledge established in earlier decades. The use of advanced engineering techniques for understanding energy transfer are also growing that avoid contradicting the laws of thermodynamics that are critical to biofuel production.

The early US-Japan collaborations documented in this review highlight the importance of people to the ongoing development of algal biofuels research. The names of Vannevar Bush and Hiroshi Tamiya are mostly forgotten. Many others are also forgotten. The know-how that resides with individuals is also often overlooked. When these individuals eventually retire or die, it is easily lost. The time gaps between key US algal publications shown in Fig. 12 point to how this can impact research outcomes. There is no question that such publications advance knowledge. It points to the ongoing necessity to think beyond the published written literature to capture in other ways individual practices and document experiences over time.

The review points to ways that collaborations are critical for sharing knowledge. Early collaborations between scientists that occurred across disciplines and international boundaries in the 1950s were vital to progress in algal research. While keywords in literature searches are helpful, we often do not know where the gaps are and such collaborations help to identify them. Collaborations continue to occur through BETO research projects and conferences such as Algal BBB. The author's own experience of collaborative work with US organizations, the US Department of Energy and scholars in Japan and Australia is just one case of how it can be an amazing journey of science and friendship.

Finally, the review has demonstrated the importance of private reports, personal communications and archives for preserving knowledge. The case of the early US-Japan collaborations reveals how they can contain insights into prior knowledge and contextualize research practices. It has also shown that these sources can easily be overlooked, forgotten, or even worse, access denied. Many government departments such as NASA, public research institutions and university libraries are systematically making historical archives accessible online. However, what will happen to the "hidden gems" when the filing cabinets in so many institutions, national laboratories, faculty offices, or private corporations are removed, researchers' computers become obsolete, or space for storage is downsized? Accessing these sources should become a standard part of every researcher's techniques. Whose responsibility it is to save and conserve this primary material remains unclear.

Declarations

An earlier version of the article was presented as a Plenary Lecture at the 10th Annual Conference of Algal Biomass, Biofuels and Bioproducts (online) on June 14, 2021. The opinions and perspectives expressed in this article should not be construed as representing the opinions or policies of any past or current government organizations, especially the US Department of Energy. They represent the author's opinions that arise from a confluence of personal roots, including my lifetime involvement with Japan and professional routes. No conflicts, informed consent, or human or animal rights are applicable to this study. The author is the sole contributor to this article.

Declaration of competing interest

The author declares that she has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

With sincere thanks to the Carnegie Institution of Washington DC, Smithsonian Institution Washington DC, the Bradbury Science Museum in Los Alamos and the University of Tokyo for access to archives that have provided a critical focus of this review. I would also like to thank the US Department of Energy (BETO) for the privilege of participating in three algal biofuels projects, National Alliance for Advanced Biofuels and Bioproducts, ABY 1 (REAP) and TABB (PACE). My special thanks to Dr. Justine Ulmann and Dr. José Olivares.

Part of the research was conducted while an employee of the University of Adelaide. This research, however, did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.algal.2021.102527.

References

[1] J. S. Burlew (ed.). Algal Culture: From Laboratory to Pilot Plant. Washington D.C.: Carnegie Institution of Washington Publication 600. Washington D.C.: Carnegie Institution of Washington. [Online] Available: https://babel.hathitrust.org/cgi/pt?id=uc1.b4193712&view=1up&seq=9&skin=2021.
[2] J. Sheehan, T. Dunahay, J. Benemann, P. Roessler, A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae. Close-Out Report. National Renewable Energy Laboratory. Golden, Colorado. NREL/TP-580-24190 [Online] Available:, 1998 https://doi.org/10.2172/15003040.
[3] J. Ferrell, V. Sarisky-Reed, National Algal Biofuels Technology Roadmap. Department of Energy, Office of Energy Efficiency and Renewable Energy, Biomass Program. DOE/EE-03324329 [Online] Available:, 2010 https://doi.org/10.2172/1218560.
[4] J.A. Olivares, et al., National Alliance for Algal Biofuels and Bio-products Final Technical Report. Donald Danforth Plant Science Center, St. Louis Missouri. DOE-DANF-03046 [Online] Available:, 2014 https://doi.org/10.2172/1166710.
[5] E.W. Becker, Microalgae. Biotechnology and Microbiology, Cambridge University, Cambridge, 1994, p. 1.
[6] M.A. Borowitzka, Energy from microalgae: a short history, in: M.A. Borowitzka, N. R. Moheimani (Eds.), Algae for Biofuels and Energy, Springer Science and Business Media, Dordrecht, 2013, pp. 1–15.
[7] Carnegie Institution of Washington Year Book, Carnegie Institution of Washington. (Vols. 1–99) [Online]. Available: https://carnegiescience.edu/carnegie-institution-year-books-numbers-1-through-99-years-1902-through-2000, 1902–2000.
[8] Studies from the Tokugawa Institute, The Tokugawa Institute for Biological Research, Tokyo, 1924–1963 (Vols. I-X).
[9] R. Harder, H. von Witsch, Die Massenkulture von Diatomeen. Berichte der Deutschen Botanischen Gesellschaft vol. 60, 1942, pp. 146–152.
[10] Kamakura and early algology, National Museum of Nature and Science, Tokyo [Online]. Available: http://www.kahaku.go.jp/research/db/botany/seaweeds_kamakura/English/okamura.html.
[11] K. Okamura, Icones of Japanese Algae. Scholar Select, Palala Press, 2015.
[12] Kagaku Asahi (Ed.), A Family of Noble Biologists, Asahi Shimbun, Tokyo, 1991 (In Japanese).
[13] H. Tamiya, H. Huzusige, Comparison of inhibitory phenomena in photosynthesis and catalytic decomposition of hydrogen peroxide, Kagaku 12 (9) (1942) (In Japanese).
[14] H. Tamiya, H. Huzusige, S. Mii, Kinetic analysis of the dark reaction of photosynthesis, Kagaku 12 (10) (1942) (In Japanese).
[15] H. Tamiya, Über die Peroxydase in Algen, Planta, Archiv für wissenschaftliche Botanik. 23 (1–2) (1934) 284–288.
[16] A. Mituya, T. Nyunoya, H. Tamiya, Pre-pilot experiments on algal mass culture, in: J.S. Burlew (Ed.), Algal Culture: From Laboratory to Pilot Plant. Publication 600, Carnegie Institution of Washington, Washington D.C., 1953, pp. 273–281.
[17] R. Emerson, W. Arnold, The photochemical reaction in photosynthesis, J. Gen. Physiol. 16 (1932) 191–205.
[18] B. Ketchum, A. Redfield, A method for maintaining a continuous supply of marine diatoms by culture, Biol. Bull. 75 (1) (1938) 165–169.
[19] Carnegie Institution of Washington Year Book No. 41, July 1 1941–June 30 1942.
[20] Carnegie Institution of Washington Year Book No. 42, July 1 1942–June 30 1943.
[21] Carnegie Institution of Washington Year Book No. 43, July 1 1943–June 30 1944.
[22] Carnegie Institution of Washington Year Book No. 44, July 1 1944–June 30 1945.
[23] Carnegie Institution of Washington Year Book No. 45, July 1 1945–June 30 1946.
[24] H.A. Spoehr, H.W. Milner, The chemical composition of *Chlorella*; effect of environmental conditions, Plant Physiol. 24 (1949) 120–149.
[25] H.A. Spoehr, H.W. Milner, *Chlorella* as a source of food, in: Carnegie Institution of Washington Year Book No. 47, 1948, pp. 100–103.
[26] Carnegie Institution of Washington Year Book No. 51, July 1 1951–June 30 1952.
[27] Carnegie Institution of Washington Year Book No. 48, July 1 1948–June 30 1949.
[28] Carnegie Institution of Washington Year Book No. 49, July 1 1949–June 30 1950.
[29] J.B. Weisner, Vannevar Bush 1890–1974: A Biographical Memoir, National Academy of Sciences, Washington D.C., 1979.
[30] A.A. Benson, Hiroshi Tamiya 1903–1984: A Biographical Memoir, National Academies Press, Washington D.C., 2005.
[31] R. Porter (Ed.), Bush, Vannevar (1890–1974). Hutchinson Dictionary of Scientific Biography, Helicon Publishing, Oxford, 2005.
[32] Source: [Online] Available: https://www.osti.gov/opennet/manhattan-project-history/Events/1942/groves_med.htm.
[33] Source: Bradbury Science Museum, Los Alamos.
[34] S. Miyachi, Hiroshi Tamiya (1903–1984), Ber. Deut. Bot. Ges. 99 (1) (1986) 133–135.
[35] H. Tamiya, H. Huzisige, S. Mii, Kinetic analysis of the mechanism of the dark reaction of photosynthesis on the basis of temperature rate relationships, Botanical Magazine (Tokyo) 61 (1948) 39–44.
[36] H. Tamiya, H. Huzisige, The effect of oxygen on the dark reaction of photosynthesis, Acta Phytochimica 15 (1) (1949) 83–104.
[37] M. Honda, Suzuki Changed My Life, Summy-Birchard Co., Evanston, Illinois, 1976, p. 106.
[38] W.H. Coaldrake (Ed.), Japan from War to Peace: The Coaldrake Records (1939–1956), Routledge, London, 2003 (Compiler and editor).
[39] H. Tamiya, K. Shibata, T. Sasa, T. Iwamura, Y. Morimura, Effect of diurnally intermittent illumination on the growth and some cellular characteristics of *Chlorella*, in: J.S. Burlew (Ed.), Algal Culture: From Laboratory to Pilot Plant, 1953, pp. 76–84 (Washington D.C.: Carnegie Institution of Washington Publication 600. Washington D.C.: Carnegie Institution of Washington).
[40] H. Tamiya, E. Hase, K. Shibata, T. Iwamura, T. Nihei, T. Sasa, Kinetics of growth of *Chlorella* with special reference to its dependence on quantity of available light and on temperature, in: J.S. Burlew (Ed.), Algal Culture: From Laboratory to Pilot Plant, 1953, pp. 204–235 (Washington D.C.: Carnegie Institution of Washington Publication 600. Washington D.C.: Carnegie Institution of Washington).
[41] A. Mituya, T. Nyunoya, H. Tamiya, Pre-pilot-plant experiments on algal mass culture, in: J.S. Burlew (Ed.), Algal Culture: From Laboratory to Pilot Plant, 1953, pp. 273–284 (Washington D.C.: Carnegie Institution of Washington Publication 600. Washington D.C.: Carnegie Institution of Washington).
[42] A.W. Fisher Jr., J.S. Burlew, Nutritional value of microscopic algae, in: J.S. Burlew (Ed.), Algal Culture: From Laboratory to Pilot Plant, 1953, pp. 303–310 (Washington D.C.: Carnegie Institution of Washington Publication 600. Washington D.C.: Carnegie Institution of Washington).
[43] Algal Research [Online] Available: https://www.journal.elsevier.com/algal-research.
[44] G. Simon, Food security: definition, four dimensions, history [Online] Available: http://www.fao.org/fileadmin/templates/ERP/uni/F4D.pdf, 2012.
[45] Public Law 165/Chapter 479 [Online] Available: https://www.govinfo.gov/content/pkg/STATUTE-65/pdf/STATUTE-65-Pg373.pdf.
[46] Y. Morimura, N. Tamiya, Preliminary experiments in the use of *Chlorella* as human food, Technology 8 (4) (1954) 179–182.
[47] H. Tamiya, Mass culture of algae, Annu. Rev. Plant Physiol. 8 (1957) 309–344.
[48] R. Davis, B. Klein, Algal biomass production via open pond algae farm cultivation: 2020 State of technology and future research, National Renewable Energy Laboratory, Golden, Colorado, 2021. https://doi.org/10.2172/178490. NREL/TP-5100-79931, p. 8 [Online] Available:.
[49] A. Schwab, Bioenergy Technologies Office Multi-year Program Plan. DOE/EE-13857369 N.p [Online] Available:, 2016 https://doi.org/10.2172/1245338.
[50] S.M.A. Mobin, H. Chowdhury, F. Alam, Commercially important bioproducts from microalgae and their current applications — a review, Energy Procedia 160 (2019) 752–760.
[51] Japanese Society of Plant Physiologists (Ed.), Studies on Microalgae and Photosynthetic Bacteria. A Collection of Papers Dedicated to Hiroshi Tamiya on the Occasion of his 60th Birthday. Special Issue of Plant and Cell Physiology, University of Tokyo Press, Tokyo, 1963.
[52] L. Machlis, Review: Tamiya volume, Science (American Association for the Advancement of Science) 141 (1963) 514–515.
[53] H. Tamiya, Synchronous cultures of algae, Annu. Rev. Plant Physiol. 17 (1966) 1–27.
[54] Chlorella Industry Co. Ltd [Online] Available: https://www/chlorella.co.jp/company/profile/.
[55] Euglena [Online] Available: https://www.euglena.jp.en/businessrd/.