PHAGE: Therapy, Applications, and Research
Volume 3, Number 4, 2022

DOI: 10.1089/phage.2022.29037.inp

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A Brief History of Phage Research and Teaching in Africa

Tobi E. Nagel, PhD,[1] Ivy J. Mutai, BSc,[2] Theodore Josephs, MSc,[3] and Martha R.J. Clokie, PhD[3]

Introduction

While the global community was shocked by the impact of COVID-19 and the 3.56 million deaths it caused worldwide in 2021, the pandemic of antimicrobial resistance (AMR) was already linked to even more deaths each year.[1] Indeed, a recent study estimated that in 2019, 4.95 million deaths were associated with bacterial AMR—and by 2050, the death toll from AMR is expected to rise to 10 million annually.[2,3] Predictions indicate that the African continent will have the highest AMR per capita mortality rate globally, with 4.15 million deaths expected there. This is likely due to misuse of antibiotics in both people and animals around the world, combined with the natural ability of bacteria to evolve. Since antibiotics are failing to kill pathogenic bacteria at alarmingly increasing rates, antibiotic alternatives such as bacteriophages (phages) are urgently needed worldwide, but particularly in Africa.[4]

As naturally occurring agents that can kill antibiotic-resistant bacteria, phages could provide important tools to combat AMR. And since phages are relatively easy to isolate from commonplace environments such as sewage, they are well suited for development in under-resourced nations. This is important because during pandemics, low- and middle-income countries typically receive essential medicines much later than high-income countries do, as was observed with the global distribution of COVID-19 vaccines. Thus, there is a pressing need to build up AMR drug development expertise in Africa. This was the primary reason the nonprofit organization Phages for Global Health (PGH) chose the African continent as a first destination for training and collaboration on phage projects. Importantly, since far less is known about phages isolated in Africa than in Europe and North America, it is highly likely that unique phages will be discovered in Africa, which may enable African scientists to develop novel phage-based drugs there.

In this inPhocus article we summarize the evolution of phage research in Africa to date, including the initial publications, how training programs have helped to accelerate work there, the types of phage applications that African scientists are exploring in aquaculture, livestock, crops and human health, and new collaborative networks that have emerged to support those efforts. We also discuss the current hurdles many African researchers encounter and highlight ways those limitations might be overcome.

Initial Phage Research in Africa

To our knowledge, the first report in English of phage isolation in Africa by local scientists was published in 1958 by J.N. Coetzee from the University of Pretoria in South Africa, and it described the characterization of a set of *Proteus* phages.[5] Between then and 1988 Coetzee and collaborators published at least 50 articles on phages, focusing mostly on *Proteus* species, but also including phages targeting *Lactobacillus*, *Serratia*, *Salmonella*, *Escherichia coli*, *Rhodococcus*, and *Klebsiella* bacteria.[5–11] The work included host range evaluation, microscopic structural analyses, and studies of lysogenic conversion as well as transduction. In 2019, a genus of phages, *Coetzeevirus*, was named in honor of his large body of work.

Between 1990 and 2002 two groups in Egypt reported on the isolation of novel phages. The first team, from Ain Shams University in Egypt, published several articles characterizing phages targeting *Bacillus thuringienses* and *Bacillus sphaericus*. These bacteria have the beneficial effect of killing mosquito larvae, and the researchers demonstrated that the phages inhibited that larvicidal activity.[11–14] In 2001, another group at Zagazig University in Egypt isolated and characterized a set of phages against *Streptomyces scabies*, a bacteria that causes scab disease in potatoes.[16]

The next two reports of phage characterization by African scientists were published in 2011. The first characterized 14 samples with *Lactobacillus* phages obtained from vaginal samples of patients in South Africa and was authored by researchers at the South African National Institute for Communicable Diseases and the University of Witwatersrand.[17] In the second report, enrichment for phages was conducted by scientists at the University of Lagos in Nigeria, then electron microscopy was performed at Laval University

[1]Phages for Global Health, Oakland, California, USA.
[2]Institute of Primate Research, Nairobi, Kenya.
[3]Department of Genetics and Genome Biology, University of Leicester, Leicester, United Kingdom.

in Canada, with a total of 15 phages being identified.[18] The next publication came in 2013, in which researchers in Egypt characterized three soil-derived actinophages that targeted *Streptomyces flavovirens*.[19]

For the next few years, articles began to emerge that focused on isolating phages for eventual biocontrol of pathogenic bacteria. The first of those was published in 2014 by scientists at the University of Nairobi and the Kenya Medical Research Institute (KEMRI), with transmission electron microscopy (TEM) conducted at the Wellcome Sanger Institute in the United Kingdom.[20] That work targeted *Vibrio cholerae* and included the characterization of nine phages isolated from the Lake Victoria region in Kenya through enrichment using a *V. cholerae* strain that had been previously isolated from the same region.

The following year scientists at Benha University in Egypt published a report describing the isolation, formulation, and testing of *Xanthomonas axonopodis* phages to decrease bacterial blight on pepper plants. As compared with unformulated phages, treatment with the formulated phages significantly decreased disease severity and lesion spots on plants in both greenhouse and open field tests.[21]

Also in 2015, two separate groups of researchers in Egypt and Cote d'Ivoire isolated phages with activity against *Pseudomonas aeruginosa* isolates derived from cystic fibrosis patients.[22,23] The Egyptian group demonstrated phage activity against multidrug-resistant (MDR) bacteria, whereas the Ivorian group, who worked in collaboration with French colleagues, focused on identifying phages that could kill strains previously known to be resistant to a large set of phages. In addition, genomic characterization of the 22 Ivorian phages demonstrated significant phage diversity, even when derived from a limited geographic area.

In 2016, the first African study testing phage efficacy in a mouse model was published by scientists at the Institute of Primate Research (IPR) in Kenya. Using an MDR *Staphylococcus aureus* strain that had been isolated from contaminated environmental samples in Nairobi, the authors demonstrated that phages isolated from similar samples could significantly decrease intravenous bacterial levels when given 24 or 72 h after experimental infection.[24]

Two different South African groups also published articles in 2016 describing unique types of phages. Msimbira et al isolated *Bradyrhizobia*-targeting rhizobiophages from groundnuts.[25] *Bradyrhizobia* are symbiotes that reside in groundnut nodules and help the plants grow by fixing nitrogen. Thus, this is a peculiar situation in which phages can harm the plants by killing the bacteria. Van Zyl et al isolated phages from soda lakes in Kenya and Ethiopia.[26] These are bodies of water with halo-alkaline environments, and the novel phages targeted bacteria that most closely resemble *Bacillus* and *Paracoccus* strains.

As DNA sequencing technologies have advanced, several research groups have genomically characterized phages in wastewater or as part of ecological or environmental studies, without actually isolating them. For example, work by scientists in South Africa revealed for the first time the diversity of the viral community within Namib Desert hypoliths.[27] For the remainder of this article, we will focus the discussion on research that has explicitly included physical isolation of phages.

Laboratory Training Workshops

In 2008, the Howard Hughes Medical Research Institute (HHMI) in the United States and University of KwaZulu-Natal (UKZN) in South Africa initiated a collaboration that resulted in the establishment of the Kwazulu-Natal Research Institute for Tuberculosis and HIV (K-RITH) in South Africa. As part of that collaboration, faculty and staff from the University of Pittsburgh (Graham Hatfull and Deborah Jacobs-Sera), the Albert Einstein College of Medicine (William Jacobs and Michelle Larsen) K-ROHITH (Victoria Kasprowicz), UKZN (Bala Pillai, and Hafizah chennai), and the Harvard School of Public Health (Cric Rubin) delivered a series of hands-on phage workshops at UKZN. Those workshops ran for 2 weeks each year between 2008 and 2018, and the goal was to provide a practical research experience for young scientists by having them work directly with phages. Given K-RITH's focus on tuberculosis, the workshop utilized *Mycobacterium smegmatis* as the bacterial host for isolating mycobacteriophages. Approximately 25 students participated in each workshop, mostly K-RITH fourth year undergraduate students and some graduate students. During the mornings the participants isolated and purified mycobacteriophages, and during the afternoons they learned how to annotate the genomes of mycobacteriophages that had been isolated in previous workshops.

More than 200 students were trained through these workshops, and an initial publication from that work came out in 2014 describing the genomic and proteomic characterization of a set of mycobacteriophages.[28] One of the mycobacteriophages isolated through those workshops was named ''Muddy,'' and it has become an extremely valuable phage that has been used in clinical settings, including to extend the life of a patient in a highly publicized case at Great Ormond Street Hospital in London.[29]

In 2017, the U.S.-based charity organization PGH began delivering in-country phage workshops, first in East Africa, then expanding to West Africa (and eventually also to Southeast Asia).[30] The goals of these workshops have been to provide education about how phages might be used to address the AMR crisis in those regions and also to establish relationships among a network of phage researchers in Africa. Similar to the K-RITH-associated workshops, each PGH workshop ran for 2 weeks and included roughly 25 participants. However, the PGH workshop participants came from countries throughout each region (East Africa or West Africa) and included scientists across a broad range of career levels (undergraduate and graduate students, laboratory technicians, university lecturers, and administrators), with the participants being selected through a competitive application process. By including scientists at all career levels, the aim has been to empower senior academic leaders who have the authority and resources to lead phage research programs while also providing younger scientists with the hands-on skills needed to integrate phage research into their developing careers.

The instructors for the PGH workshops have included experts in different aspects of phage therapy and have come from the University of Leicester in the United Kingdom (Martha Clokie and Janet Nale), Yale University in the United States (Benjamin Chan), the University of Zurich in Switzerland (Shawna McCallin) and PGH (Tobi Nagel).

During the mornings the instructors gave lectures on key aspects of phage biology, as well as on potential antibacterial applications in food crops, animals, and people. In the afternoons the participants isolated phages and began to characterize them experimentally, with a brief introduction to relevant bioinformatics tools. *P. aeruginosa* and *E. coli* were used as the host bacteria since it is relatively easy to isolate the associated phages. The first workshop was hosted at Makerere University in Uganda, and subsequent workshops were held at Pwani University in collaboration with IPR in Kenya (2018), Kwame Nkrumah University of Science and Technology in Ghana (2019), and Muhimbili University of Health and Allied Sciences in Tanzania (2020). A total of 93 participants were trained through the four workshops, including from five countries in East Africa (Ethiopia, Kenya, Rwanda, Tanzania, and Uganda) and seven in West Africa (Benin, Cote d'Ivoire, The Gambia, Ghana, Nigeria, Senegal, and Togo).

To quantify the impacts of the workshops, PGH polled the participants beginning 3 months after each workshop, then yearly thereafter (except during the COVID-19 pandemic) to learn about their ongoing teaching and research in phage biology, as well as their associated grant writing activities. Thus far, the participants have taught the basics of phage biology to $\sim$1200 others through their home institutions; have initiated at least 50 phage research projects; and have won grants totaling >$945,000. Now that the worst of the COVID-19 pandemic appears to be over, PGH plans to run more in-person workshops in East and West Africa, with the long-term goal being to eventually deliver workshops in other regions of Africa (as well as in Southeast Asia).

Additional in-country phage training programs have emerged in Nigeria, Kenya, and Uganda. When the K-RITH-associated workshops began in South Africa, HHMI also launched the SEA-PHAGES program, which is a two semester course through which cohorts of undergraduate students learn how to isolate phages during one semester and annotate phage DNA during the other semester. SEA-PHAGES began at educational institutions in the United States, but two universities in Nigeria eventually joined the program: the University of Lagos in 2017 and the University of Ibadan in 2018. In Lagos the SEA-PHAGES team led by Imade Nsa has 4 faculty members and has taught 91 students, and in Ibadan a team of 8 faculty members led by George Ademowo has taught 41 students. Owing to national strikes in Nigeria that have disrupted educational systems, most of the SEA-PHAGES teaching at both institutions has focused on the bioinformatics component of the course.

In 2017, IPR in Kenya began teaching interns how to isolate and test phages, and they significantly expanded their training program in 2018 after several members of the IPR team had attended the PGH workshops in Uganda and Kenya. Many interns do short rotations at IPR as part of their education, so IPR has typically taught cohorts of 4–5 students for 1–2 months at a time, usually using *E. coli* as the host. To date more than 150 researchers have been trained through the IPR program, including scientists from other parts of sub-Saharan Africa, as well as those from institutions throughout Kenya. The instructors have included Joseph Oduor, Ivy Mutai, Angela Juma, and Dennis Kotti, with Atunga Nyachieo overseeing the program, particularly with regard to *in vivo* protocols for testing phages.

Makerere University in Uganda, which was the host institution for the 2-week PGH phage workshop in 2017, delivered a 1-week version of that workshop in 2022. The 15 participants, who were all members of the Makerere University community, included mostly graduate students, as well as some undergraduates and university staff. They isolated phages using *E. coli* as the host bacteria and evaluated the DNA of previously sequenced phages. The instructional team was led by Jesca Nakavuma, and included Raphael Hans Lwesya, Alafi Stephen, and Musisi Nathan Lubowa.

Ongoing Phage Research and Product Development

Since 2017, several large projects have been initiated in Africa specifically developing phage products intended for the food industry and with funding coming from international sources. The first of those was a project focused on isolating *Campylobacter* phages in Kenya and dry powder formulating them for storage without refrigeration, intended for eventual decontamination of poultry meat. Financial support equivalent to roughly $375,000 USD was provided by the Biotechnology and Biological Sciences Research Council in the United Kingdom, with collaborators, including KEMRI, the University of Nottingham (United Kingdom), the University of Alberta (Canada), and PGH (United States). A total of 17 phages were isolated and are awaiting further characterization. This project also included funding for public engagement activities aimed at educating future phage product users, government leaders, and other stakeholders about the potential benefits of phages, as well as trying to address any questions or concerns those stakeholders might have regarding this new class of antibacterial agents. The Kenyan teammates conducted 51 focus group discussion meetings with a total of 377 poultry farmers and butchery operators.

The next large project was initiated in 2018 and is focused on developing phages to be used in the aquaculture industry, with the project thus being named SafeFish. The goal is to isolate phages targeting many different pathogenic bacteria in tilapia farms, including *Streptococcus agalactiae*, *Streptococcus iniae*, *Aeromonas*, *Edwardsiella*, *Serratia marcescens*, *Proteus*, *Lactococcus garviae*, *Yersinia ruckeri*, *Vibrio*, *Pseudomonas putida*, *Pseudomonas fluorescens*, *P. aeruginosa*, *Flexibacter*, and *Flavobacterium*. The funding, equivalent to about $800,000 USD, was provided through the European Union and the African Union. Collaborators include institutions in Uganda (Makerere University, the National Agricultural Research Organization, and the National Fisheries Resources Research Institute), Ghana (the Council for Scientific and Industrial Research, the University of Cape Coast, and the University of Ghana), and the United Kingdom (University of Leicester).

In 2018, another project evolved as a collaboration between the National Research Institute for Agriculture, Food and the Environment (INRAE) in France, the Plant Populations and Bio-aggressors in Tropical Ecosystems (PVBMT) on the island of Reunion (an official department of France), and a team at the Food and Agricultural Research and Extension Institute (FAREI) on the neighboring island nation of Mauritius. Their research focuses on *Ralstonia solanacearum*, a plant pathogen that causes bacterial wilt and significantly impacts crops on both islands. The

researchers were able to identify 10 phages from Reunion and 13 from Mauritius, which together represent 13 new species. These phages have high genetic diversity as compared with previously characterized *R. solanacearum* phages, probably owing to the remoteness of the islands on which they were identified. As an extension of that project, Clara Torres-Barcelo from INRAE delivered a 6-day training workshop in Mauritius, during which the local team of scientists amplified and purified a subset of those phages, then tested them on tomato plants in greenhouses. Optimization of a phage cocktail is ongoing.

In 2019, Canada's International Development Research Center (IDRC) and the UK's Global AMR Innovation Fund jointly provided the largest phage grant in Africa to date—equivalent of roughly $2.4 million USD—for a project to develop and spray dry *Salmonella* phages intended for poultry meat decontamination in Kenya. Collaborators include Laval University and SyntBioLab in Canada and the International Livestock Research Institute in Kenya. The project targets *Salmonella* species (*Salmonella* Enteritidis, *Salmonella* Pullorum, *Salmonella* Gallinarum, *Salmonella* Kentucky, and *Salmonella* Heidelberg). Thus far, 17 unique *Salmonella*-specific phages have been identified, with some of those being able to infect *E. coli* as well. The public engagement activities involved conducting 24 focus group discussion meetings with 162 respondents and 18 key informants, including veterinarians, agrovets, production officers, and hatchery employees.

In 2019, a new phage project focused on human treatment began at KEMRI in collaboration with the U.S. Army Medical Research Directorate-Africa, which has laboratory facilities housed within KEMRI. The goal of this project is to develop phage cocktails for treatment of combat-associated infections caused by ESKAPE bacterial pathogens, particularly *P. aeruginosa* and *Klebsiella pneumonia*. Funding is provided through the Walter Reed Army Institute of Research (WRAIR). In parallel with this project, graduate students working in the KEMRI laboratory have been isolating phages against *Enterobacter* species and *Acinetobacter baumannii*. Thus far, a total of 221 phages have been isolated and are in the process of being fully characterized.

In addition to the multinational projects described earlier, for the past 5 years a significant amount of phage research has been conducted as part of postdoctoral projects and student theses at universities and institutions across Africa, although not all of that has reached the stage of peer-reviewed publication. During this period the number of phage publications from African authors has also increased substantially: by our count, there were at least 10 articles published during the 5 years between 2011 and 2016 (as described in the ''Initial Phage Research in Africa'' section above), but the number of publications increased fivefold during the subsequent 5 years (2017–2022).

To our knowledge, scientists from nearly 90 institutions in 14 African countries have been involved in phage research (Fig. 1 and Table 1). Furthermore, >$4 million in total funding has been raised collectively by these scientists, with support coming from the organizations shown in Table 2. Topics have included many potential phage applications, such as the following:

- In people: for diseases such as tuberculosis, diabetic foot ulcers, urinary tract infections, diarrhea, and wounds (*A. baumannii*,[31] *E. cloacae*,[32,33] *Enterococcs faecalis*,[34,35] *E. coli*,[36,37] *Salmonella*,[38,39] *K. pneumoniae*,[39–43] *Mycbacterium tuberculosis*,[28,44] *P. aeruginosa*,[23,45–47] *Staphylococcus* spp.,[24,48,49] *Proteus* spp.,[50] and *Achromobacter xylosoxidans*[51]).
- In animals: including poultry, cattle, pigs, and gorillas (*Campylobacter* spp.,[52] *E. coli*,[32,36,53–62] *Salmonella* spp.,[37,52,62–65] *S. aureus*, and *Bacillus anthracis*[67]).
- In fish: for tilapia and catfish (*Streptococcus* spp., *Aeromonas hydrophila*, *Edwardsiella tarda*, *S. marcescens*, *Proteus*, *L. garviae*, *Y. ruckeri*, *Vibrio*, *Pseudomonas* spp., *Flexibacter*, *Flavobacterium*, and *K. pneumoniae*[39]).
- On food products: for meats, eggs, and vegetables (*Salmonella*,[65,66,68,69] *Staphylococcus* spp.[70,71]).
- In plants: for crop pathogens (*Erwinia amylovora*,[72] *Pseudomonas syringae*,[73] *R. solanacearum*,[74–77] and *Xanthamonis* spp., and *Pectobacterium carotovorum*[78]).
- In water: for sources of drinking water and understanding ecological dynamics[79,80] (*E. coli*, *E. cloacae*, and *Vibrio* spp.[20,81,82]).

Several institutions have been particularly active in training students in phage biology. For example, under the mentorship of Jesca Nakavuma at Makerere University in Uganda, 17 students have conducted thesis research on phage topics, including at the bachelors, masters, and doctoral levels. Also, three masters students and two doctoral students have conducted their phage thesis research under the leadership of Atunga Nyachieo at the IPR in Kenya. Drs. Nakavuma and Nyachieo also served as hosts for PGH's first and second laboratory training workshops in 2017 and 2018, respectively.

In a way Egypt is a special case within Africa, given both the long history of phage research there and the fact that in recent years much phage work has been initiated by researchers at the Cairo University and Zewail City of Science and Technology. In 2012 and 2014, phage dissemination events were held at BioVision Alexandria, aimed at solving global problems such as world food supply issues and distribution of medicines. Evidence for the skills base and interest in phage biology and applications was also seen during the 2021 International Egyptian Phage Conference, hosted by organizers in Zewail City. As such, an in-depth history of phage work in Egypt will be the subject of a future inPhocus article.

Collaborative Networks in Africa

Now that there is a critical mass of phage researchers on the African continent, several official networks have formed to facilitate communication between those scientists, as well as with phage researchers elsewhere in the world. In Kenya, the team at IPR has an active social media platform through which they create awareness on AMR and the potential use of phages as antibiotic alternatives (https://twitter.com/Phages IPR and https://www.linkedin.com/in/phages-ipr-b4b429253/). For several years they have also facilitated regular journal clubs through which members discuss research articles on phage topics.

Since 2020, the SEA-PHAGES team at the University of Ibadan in Nigeria, which is also called the Ibadan Bacteriophage Research Team (IBRT), has hosted an annual

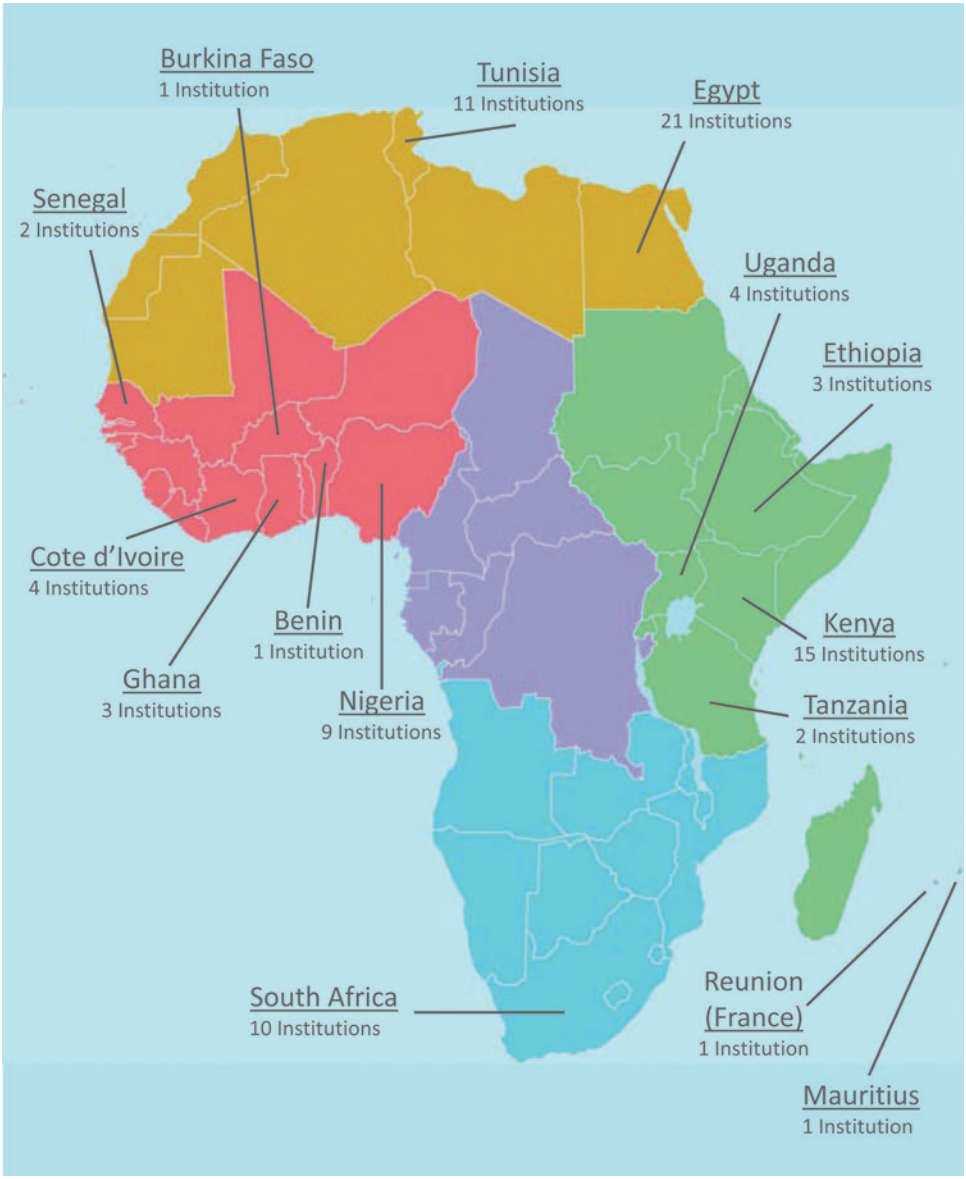

FIG. 1. Institutions in Africa where phage research has been conducted, based on a review of the literature, as well as the authors' communications with a network of African scientists (Adapted from: Ali A. Fazal, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, through Wikimedia Commons.[86]

webinar series during World Phage Week, a global initiative that aims to raise awareness about the potential benefits of phages. More recently IBRT has also established Phamilia Journal, an online journal through which the team showcases members' research abstracts, conference presentations, scientific reviews, perspective pieces, and also some publications from phage researchers in other countries. Information about those webinars and publications are communicated through the team's Twitter (https://twitter.com/IbadanPhageTeam) and LinkedIn (https://www.linkedin.com/in/ibadan-bacteriophage-research-team) accounts, as well as through their website (https://ibadanphageresearchteam.org/).

Researchers from several countries in East and West Africa came together in 2020 to establish the Africa Phage Forum (APF), a network aimed at helping to advance phage research across the African continent. Members seek solutions to common challenges faced by phage scientists in low- and middle-income countries, and APF has established several social media platforms aimed at encouraging collaboration, scholarship, and mentorship (https://twitter.com/PhageForum; https://www.linkedin.com/pulse/african-phage-forum-angela-makumi/; https://africaphageforum.org/). APF hosts a series of webinars with presentations from phage experts around the world (https://apf.phage.directory/) and with technical and logistical support provided by Phage Directory (https://phage.directory/). Through a WhatsApp group, members also share experimental protocols, scientific articles, and information about funding and job opportunities.

In March 2022, phage researchers met in Nairobi for the first national phage meeting hosted anywhere in Africa. This one-day symposium, entitled the ''Status of Bacteriophage Research in Kenya,'' was cohosted by KEMRI and IPR. Sixty participants from 14 national and international institutions attended, with speakers highlighting their phage research on a wide range of topics, including antibacterial applications in people, poultry, and aquaculture, utilizing phages in pathogen detection, formulating phages, and also endolysins. The goals were to understand the existing capacity for phage research in Kenya and set the stage for future collaborations,

Table 1. Institutions in Africa That Have Been Involved in Phage Research*

Country	*Institution*
Benin	University of Abomey-Calavi
Burkina Faso	Souro-Sanou Teaching Hospital
Cote d'Ivoire	Pasteur Institute of Cote d'Ivoire
	University of Peleforo Gon Coulibaly
	Félix Houphouët-Boigny University
	National Public Health Laboratory
Egypt	Ain Shams University
	Helwan University
	University of Science and Technology, Zewail City of Science and Technology
	Arish University
	Zagazig University
	Suez Canal University
	October University for Modern Sciences and Arts
	National Research Centre
	Mansoura University
	Alexandria University
	Cairo University
	Children's Cancer Hospital Egypt
	Benha University
	Suez Canal University
	Ministry of Agriculture and Land Reclamation
	Central Administration of Plant Quarantine
	Minia University
	Deraya University
	Al-Azhar University
	Animal Health Research Institute
	Taif University
Ethiopia	Jimma University
	Wollega University
	St Paul's Hospital Millennium Medical College
Ghana	Council for Scientific and Industrial Research (CSIR)—Food Research Institute
	University of Ghana
	Kwame Nkrumah University of Science and Technology
Kenya	Technical University of Kenya
	University of Nairobi
	Kenya Medical Research Institute (KEMRI)
	US Army Medical Research Directorate—Africa
	Institute of Primate Research
	Pan African University Institute for Basic Sciences Technology and Innovation (PAUSTI)
	Consultative Group for International Agricultural Research (CGIAR)—Antimicrobial Resistance Hub/International Livestock Research Institute (ILRI)
	Sino-Africa Joint Research Centre
	Jomo Kenyatta University of Agriculture and Technology
	Taita Taveta University College
	Kenyatta University
	Pwani University
	Kenya Marine and Fisheries Research Institute
	Kisii University
	Ministry of Agriculture, Livestock, Fisheries and Cooperatives
Mauritius	Food and Agricultural Research and Extension Institute (FAREI)
Nigeria	National Veterinary Research Institute
	University of Lagos
	University of Jos
	Plateau State University
	Michael Okpara University of Agriculture
	Nigeria Centre for Disease Control
	University of Nigeria
	Ahmadu Bello University
	Abubakar Tafawa Balewa University Bauchi
Reunion (France)	Plant Populations and Bio-aggressors in Tropical Ecosystems (PVBMT)
Senegal	University Cheikh Anta Diop Dakar
	Pasteur Institute of Dakar
South Africa	North-West University
	University of Mpumalanga
	National Institute for Communicable Diseases (NHLS)
	University of the Witwatersrand
	Stellenbosch University
	University of KwaZulu-Natal
	University of Pretoria
	University of the Western Cape
	University of Cape Town
	Tshwane University
Tanzania	Kilimanjaro Christian Medical University College
	Sokoine University of Agriculture
Tunisia	INRA Tunisia, University of Carthage
	University of Tunis El Manar
	Water Research & Technology Center (CERTE)
	National Agronomic Institute of Tunisia, University of Carthage
	Military Hospital of Instruction of Tunis
	University of Sfax
	Tanta University
	Olive Tree Institute
	Agrovet
	University of Monastir
	National Center for Nuclear Sciences and Technologies (CNSTN)
Uganda	Makerere University
	Kampala International University
	Kyambogo University
	Clarke International University

*Based on a Review of the Literature, As Well As the Authors' Communications with a Network of African Scientists

Table 2. Organizations That Have Provided Funding for Phage Research and Teaching in Africa

African Union
Bill and Melinda Gates Foundation
Biotechnology and Biological Sciences Research Council (BBSRC)
Carnegie Corporation of New York
Cooperation and Cultural Action Service (SCAC)
Conservation, Food and Health Foundation
Department of Science and Technology of South Africa
European and Developing Countries Clinical Trials Partnership (EDCTP)
European Union
Fogarty International Center—US National Institutes of Health (NIH)
Global AMR Innovation Fund
International Development Research Center (IDRC)
International Foundation for Science
Islamic Development Bank
Makerere University—Research and Innovations Fund
Microbiology Society
Mozilla Foundation
National Research Foundation of South Africa
Organization for Women in Science for the Developing World (OWSD)
Stellenbosch Institute for Advanced Study
Swedish International Development Cooperation Agency (SIDA)
The Company of Biologists
The Special Programme for Research and Training in Tropical Diseases (TDR)
The World Academy of Sciences (TWAS)
Tshwane University of Technology
UK Research and Innovation (UKRI)
West Africa Research Association
World Bank

including potentially establishing a centralized national phage collection. There was significant media coverage, with representatives from multiple newspapers and reporting agencies attending. The symposium led to the formation of the Phage Kenya Consortium, with its main aims being to create a scientific community that builds repositories of phages intended for a spectrum of One Health applications. The consortium also raises awareness about phage research, advocating for the safe use of phages in animals, food industries, and health care. A Phage Kenya website is under development and will serve as a central site for sharing information about funding and training opportunities, as well as for consolidating standard operating procedures for phage research. The consortium has established Twitter and LinkedIn accounts as avenues for communication (https://twitter.com/PhageKenya; https://www.linkedin.com/in/phage-kenya-consortium-386246257/).

Current Needs and Next Steps

Based on all the activities described earlier, there is clearly an appetite to continue to expand phage research in Africa. However, to fully characterize and test new phages, many scientists require access to facilities and services outside of their institutions and countries. This includes help with sequencing and annotation of phage genomes and also with TEM imaging. Although DNA can be sent away to companies that provide sequencing services, unreliable or very expensive postage can mean that it is not trivial to access those services. Furthermore, there is a general hunger to receive further education on how to annotate and compare phage genomes. Toward this end, there are many good articles on new techniques that can be utilized.[83–85] Regarding TEM imaging, there are very few facilities in Africa, and although several places worldwide have such facilities, accessing them can be cost prohibitive. In the long-term, having local access to TEM would be incredibly valuable.

Obtaining adequate funding for research and product development is also challenging. Although the list of agencies that have provided financial support for phage researchers in Africa is substantial (as shown in Table 1), the amount available to individual scientists and institutions is still quite lacking when spread across the entire continent. Many African scientists struggle to secure essential laboratory supplies, occasionally paying for those from personal funds. Thus, there is a significant need to increase international funding for research in Africa. In addition, more training in grantsmanship might help improve scientists' success in accessing the necessary financial support.

Even though phage expertise is developing across Africa, those wishing to conduct doctoral thesis research in phage biology have often chosen to go overseas to receive appropriate mentoring. To date, African phage researchers have sought graduate training in Belgium, China, Finland, France, Malaysia, Pakistan, Sweden, the United Kingdom, and the United States, with the funding typically provided by those countries or international agencies. Such foreign exchanges can also aid in establishing long-term collaborative relationships. Toward that end, the collaborative networks described in the preceding section and also PGH can serve to connect scientists from different countries, enabling them to more easily identify common research interests.

Phage products can be valuable assets for Africa, providing tools to combat antibiotic-resistant bacteria in people, animals, aquaculture, and crops. In so doing, phages could not only help save lives, but also bolster national economies. Building up scientific capacity to develop such products within Africa will be vitally important, particularly since the African continent is expected to experience the world's highest per capita mortality rate from AMR infections.

Acknowledgments

We are grateful for the inputs from numerous people, which helped in the writing of this article, including George Ademowo, Olubusuyi Moses Adewumi, Evelien Adriaenssens, Benjamin Chan, Graham Hatfull, Deborah Jacobs-Sera, Angela Juma, Andrew Kropinski, Raphael Hans Lwesya, Sylvain Moineau, Lillian Musila, Jesca Nakavuma, Mikeljon Nikolich, Imade Nsa, Atunga Nyachieo, Erick Odoyo, Tolulope Oduselu, Jessica Sacher, Vic Sivanathan, Nicholas Svitek, Clara Torres-Barcelo, and Jan Zheng.

Author Disclosure Statement

No competing financial interests exist.

Funding Information

No funding was received for this article.

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Address correspondence to:
Tobi E. Nagel, PhD
Phages for Global Health
383 62nd Street
Oakland, CA 94618
USA

Email: tobi@phagesforglobalhealth.org