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From laboratory to laptop: How science communication can bridge the gap between plant pathology and the public

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ABSTRACT

This paper briefly summarizes my favorite highlights of the plant pathology research presented at the 12th Japan-US Seminar in Plant Pathology and hones in on the associated panel discussion in which career professionals in the field of plant science were probed for their observations on a series of topics that are popular amongst scientists from all disciplines around the world. Panelists highlighted the pros and cons of social media, publications, academic networking platforms, literature corrections, and scientific communication in a variety of contexts as well as the challenges marginalized groups experience in science. Here, I synthesize the recent research progress of American and Japanese plant pathologists, as well as panelists' observations and audience members' comments with peer-reviewed literature and provide extra resources and recommendations that I hope will help readers to achieve success in, and out, of academia and science.

1. Introduction

The global development and growth of science over the past decade owes itself to new discoveries, innovative technologies, and a greater understanding of how inextricably intertwined fields of science are with each other. The development and growth of science is due in large part to the evolution of scientific communication and wider dissemination of scientific findings to scientists and non-scientists alike. This remarkable progress in science has been demonstrated through societal, political, and economic transformations. Society needs science as a driver for social, economic, and political success, while science thrives in part due to the services, products, and freedoms that the society makes available. Thus, as science progresses, societal changes occur, and issues arise at the interface of science and society. We must discuss these issues to resolve them for future generations of scientists and non-scientists.

2. A short summary of molecular plant pathology research presented at the 12th JUSPP

In late August of 2022, the 12th iteration of the Japan-U.S. Seminar in Plant Pathology (JUSPP) was hosted by Cornell University. Around 100 plant pathologists from Japan and the United States congregated for the first time since 2015 to present their research on a range of topics fitting the theme of "Remodeling of the Plant-Microbe Environment During Disease, Defense, and Mutualism". As one of the recipients of the Early Career Participation Award, I was tasked with posting tweets about the various scientific research being presented at the meeting. Here, I will summarize some of the research findings that I found, personally, to be the most enticing and revolutionary to the future of plant pathology.

Plants and pathogens are in a never-ending evolutionary arms race where the plants defends themselves against the pathogens and the pathogens aim to circumvent plant defenses to infect and cause disease. As time progresses, it is becoming increasingly difficult to protect plants from pathogens using conventional practices. In the "Defense" section, Dr. Hailing Jin presented on cross-kingdom bi-directional RNA trafficking and how small RNAs (sRNAs) can travel between interacting organisms and induce gene silencing in the opposite party. Her team has used this knowledge to develop a novel system in which double-stranded RNAs or sRNAs can be directly applied to host plants or post-harvest products to silence target pest genes and confer efficient disease control [1]. This eco-friendly strategy (i.e., environmental RNAi) is easily adaptable to control multiple diseases and it will help growers be able to fight disease more effectively in their crops. Dr. Brian Kvitko spoke about how plants defend themselves using defense phytochemical specialized metabolites. He also commented on the two-category system of phytoalexins and phytoanticipins and how non-phytoalexin phytochemicals do not fit within the current framework. Dr. Kvitko introduced a new category: phytoavengins, defensive phytochemicals synthesized from preformed constituents, typically because of tissue

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damage [2]. This proposal reshapes how we think plants counteract pathogen attack and how to study it. Dr. Adam Steinbrenner sparked our interest in innate immune receptors by discussing the recognition and signaling functions mediated by subdomains of leucine-rich repeat (LRR) type receptor-like proteins (RLPs). Based on a cryo-EM structure of an LRR-RLP, RXEG1, we can link domain architecture and sequence features of LRR-RLPs. For example, extracellular domains, transmembrane motifs, and intracellular tails can mediate processes like ligand binding, co-receptor recruitment and immune signaling specificity [3]. Steinbrenner also proposed a new motif-based classification of LRR-RLPs based on shared sequence features in the island domain.

There are multiple layers of complexity to plant-pathogen interactions and these interactions can include symbionts, plant hosts, insect vectors, plant pathogens, and a bevy of other biological players. In the "Multitrophic Interactions" section, Dr. Morgan Carter spoke about the symbiosis of *Mycetohabitans rhizoxinica* with the fungus *Rhizopus microsporus* and how proteins resembling T3-secreted transcription activator-like (TAL) effectors were found in the sequenced genomes of three *Mycetohabitans* spp. These Burkholderia TAL-like (Btl) proteins lack the canonical N- and C-terminal regions in which TAL effectors harbor their T3 and nuclear localization signals, and activation domain. A characterized Btl protein, Btl19-13, was able to be T3-secreted and localize to the nucleus despite structural differences [4]. A *btl-19-13* gene knockout did not prevent the bacterium from infecting the fungus, but the fungus became less tolerant to cell membrane stress. Dr. Michelle Heck stressed the massive threat that insect-vectored pathogens are to plant, animal, and human health and how important it is to develop strategies to block insect-vectored pathogen transmission. Systems biology studies have led to greater understanding in vector-pathogens interactions at the molecular and cellular levels and have made us rethink how pathogens interact with insect vectors [5]. Ideally, this newfound knowledge will lead to development of transmission intervention tools.

Mutualistic interactions allow both symbionts to benefit from the relationship. In the "Mutualism" section, Dr. Chikae Tatsumi informed us about how mycorrhizal fungi are drivers of biogeochemical cycling. Ectomycorrhizal (ECM) and arbuscular mycorrhizal (AM) fungi both control decomposition of soil organic matter by modifying the amount of soil nitrogen (N) available for free-living microbes, but her research showed saprotrophic fungal abundance and ammonia-oxidizing prokaryotic abundance, in addition to soil nitrate and carbon (C) content may differ in ECM versus AM forests [89]. According to Dr. Tatsumi, limitation of ECM fungi on nitrate production would result in a feedback that accelerates plant dependence on these fungi, which would cause soil C storage to increase through investments into ECM biomass and plant C. Dr. Kenro Oshima talked about phytoplasmas [87], the most poorly characterized plant pathogens, and unique features of the *Phytoplasma asteris* genome which force us to reconsider questions like "What is life?" and "How many genes are necessary for a living organism?". If a biological organism is missing genes we thought were essential to life, such as ATP synthase, how do we classify it?

Plant disease is one of the major limiting factors in global food security. In the "Disease" section, Dr. Yasufumi Hikichi presented on how the quorum sensing system in the plant-pathogenic bacterium *Ralstonia solanacearum* contributes to its virulence on tomato plants. His research group found that a mutant deficient in *ralA*, the gene that encodes furanone synthase, and produces the aryl-furanone metabolite ralfuranones, is weakly virulent when directly inoculated into tomato xylem vessels [88]. Transcriptome data uncovered that ralfuranones affect the quorum sensing feedback loop, swimming motility, and aggregation ability of the bacteria. Dr. Gitta Coaker enlightened us on how single-cell RNA sequencing (RNA-seq) technology can be used to study plant response to bacterial infection and how infection can vary within a leaf. In an experiment where *Arabidopsis* was exposed to *Pseudomonas syringae* or mock treatment, profiling of over 11,000 individual cells revealed distinct pathogen responsive cell clusters exhibiting transcriptional responses ranging from immunity to susceptibility [6]. Dr. Coaker also noted that we may be missing novel susceptibility gene candidates when using bulk RNA-seq versus single-cell RNA seq analysis.

As a scientist on the receiving end of science communication, the research mentioned above was communicated efficiently and effectively, captured my interest, and provided new insights to our overall understanding of molecular plant pathology.

3. Synthesis of the panel discussion

A panel discussion took place at the end of the 12th Japan-U.S. Seminar in Plant Pathology. The theme of this panel was "Best practices for sharing science". Panelists voiced their personal vision on subjects that affect professionals and scientists at all career stages. This discussion was moderated by Juliana González-Tobón (Cornell University), Yuta Watanabe (Okayama University), and Yumino Sasaki (Cornell University) and included the following panelists: Maria Fernanda Álvarez (Rice Program Leader, Crops for Nutrition and Health, Alliance of Biodiversity International and International Center for Tropical Agriculture (CIAT)), Morgan Carter (Assistant Professor of Biology, University of North Carolina at Charlotte), Jeanne Harris (Professor of Plant Biology, University of Vermont and Editor-in-Chief of MPMI), Sophien Kamoun (Group Leader, The Sainsbury Laboratory and Professor of Biology at the University of East Anglia), Laura Boykin Okalebo (Senior TED Fellow and Senior Scientific Consultant and Computational Biologist at Bioteam), Yoshitaka Takano (Professor of Plant Pathology, Kyoto University), and Mary Williams (Features Editor at Plant Cell and Plant Physiology, Developer of Teaching Tools in Plant Biology). The questions for the panelists focused on social media, publications, academic networking platforms, literature corrections, and scientific communication.

4. The utility of social networking tools in the scientists' toolbelt

One of the main topics was the use of social media or academic social networks (ASNs) by scientists. The use and number of social media platforms have increased dramatically in the last decade. There are more than 3.78 billion social media users worldwide and that number steadily increases year after year [7]. Social media can be used by scientists to communicate with other scientists inside or outside of their field, or with the public. The perception of social media is often mixed, with many dissenting opinions on whether it is beneficial or detrimental. The panel discussion focused on the benefits: social media is a way to boost your professional profile, give and receive support, promote openness and sharing of information, act as a public voice for science, facilitate collaboration and career advancement, or engage in fun conversation with scientists and non-scientists outside your local work environment.

Panelists first concentrated on the usefulness of ASNs (e.g., ResearchGate, Google Scholar, ORCID, academia.edu, Mendeley) and social media platforms (e.g., Twitter, Instagram, TikTok, FaceBook, LinkedIn, WhatsApp) in formal and informal scholarly communication. The value of ASNs and social media for scholarly communication is well-cited in the literature [8–13]; online tools improve research efficiency and scientific metrics and enhance professional networking. These findings agree with the general consensus among panelists: ASNs are meaningful to early career scientists for promoting your name and your research to earn future opportunities as a reviewer, collaborator or awardee. However, this does not mean that ASNs or social media are useless for late career scientists. Scientists of all ages can leverage their online presence in a plethora of ways from sharing journal articles to advertising scientific opinions, posting conference updates, or circulating information about upcoming events or opportunities [14].

The distribution of science on social media has been likened to a "nonstop academic conference for all" allowing ease of access to scientific information and the ability to observe and interact with other scientists, across a variety of platforms, such as YouTube and Twitter [15]. Improving academics' understanding of social media may increase their visibility and improve their research and/or scholarly activities. Studies have found increasing use of social networking tools and ASNs among scientists, and there is a perceived usefulness to these tools for informal scholarly communication [85]; [16]. The interconnectivity permitted by social networking sites has caused beneficial shifts in the learning and sharing environment [17–19]. Studies show that it is worth developing relevant training programs that include a focus on social media integration into research activities and their use in dissemination of research findings [20].

Despite such studies, scientists have been reluctant to communicate with the general public at the expense of focusing on academic productivity. This reluctance regarding social media use and public communication is most likely due also, at least in part, to a lack of understanding about how to use the technology. The key to using social media is who you choose to follow. As a new user, you will see sports, entertainment, music, etc., but if you 'follow' and interact with accounts that interest you or are related to your field of science, the central servers will suggest other users with similar interests which focuses what you are shown in the future [21]. A survey of highly cited U.S. nano-scientists paired with data on their social media use shows that public communication (i.e., interactions with reporters, reposts on Facebook, mentions on Twitters) can contribute to a scholar's scientific impact [22]. These findings are backed by studies from Refs. [23,24]. [23] found that, with increasing levels of activity, the number of motivations for using social media increase, as does the perceived number of successful outcomes, while [24] found that Altmetric Attention Score, an indicator of the amount and reach of the attention an article has received, was positively correlated with citation rates; thus, demonstrating the direct positive impact of social media's broad reach on academic productivity.

It should not be surprising that there is a positive relationship between internet use as a consumer and research productivity [25]; those that want to be at the forefront of their research field must be up to date with new developments. However, it is likewise important for scientists to establish a presence on the internet as a producer, and to be searchable. Participation in social media may be viewed as a waste of time or a distraction from scholarly duties, but this perception is misinformed and misinterprets how scientists manage their time and presence online. If scientists are less-established online, they may find the environment at their home institution to be less supportive, according to a study of 868 faculty members at all universities in Lower Saxony (Germany) in the disciplines of physics, biology, and chemistry [26]. [14] say that new (and long-time) users can productively use social tools in a targeted and streamlined manner by 1) exploring online guides to social media; 2) establishing a professional website (at minimum); 3) locating pertinent online conversations; 4) navigating the deluge of online information; 5) interacting with diverse participants; and 6) reaching your audience.

While the perception of social media for science communication is mostly positive, there are barriers to usage of social media such as lack of time and skills to undertake these activities and a negative general perception of social media. Negative perceptions are sometimes justified [27]. outlines some of the concerns about social media such as issues of privacy and the blurring of boundaries between personal and professional use, the risk of jeopardizing one's career through injudicious use of social media, lack of credibility, the quality of the content they posted, time pressures, social media use becoming an obligation, social media opening one to attack, too much self-promotion by others, possible plagiarism of one's ideas and the commercialization of content and copyright issues. Panelists and audience members voiced some of these same concerns during the discussion especially when referencing the spread of misinformation in a post-truth society [28]. Despite these concerns, and to address them, it is vital for scientists and non-scientists globally to become comfortable with social media and to be active participants in it to benefit from sharing of information and collaborations and to reestablish the public's trust in the scientific enterprise.

5. Challenges experienced by marginalized communities in science and science communication and how to address them

Social media is a handy tool in the scientists' toolbelt when used properly, but in some instances it can be a "see-saw" weighted by both positive and negative influences [29]. Some of the panelists spoke on the numerous challenges in science and science communication that marginalized communities encounter and how social media may be a way to reduce the number of challenges or, at the very least, expose them. Dr. Laura Boykin Okalebo commented on how social media is robust for marginalized voices and how it should be used to bring awareness to practices that inherently breed exclusivities such as financially prohibitive abstract and publication fees, VISA issues for international travel, limited research funding, and difficulty acquiring chemicals and reagents. Social media can be both convenient and powerful for disclosing these exclusivities and possibly resolving them. However, there are implicit and explicit biases in organizations and communication platforms that can adversely affect marginalized communities that people should be aware of, and I will address a few of them.

Face-to-face communication and the Internet are used to erect social networks and improve professional life. Networking behaviors are proactive attempts by individuals to develop and maintain relationships with others for the mutual benefit in their work or career. However, marginalized groups may experience difficulties in building social networks online and offline because of (1) the similarity-attraction paradigm (i.e., those who are considered similar on ascriptive characteristics are likely to perceive greater interpersonal similarities, which in turn leads to increased attraction and more frequent communication), (2) tokenism theory (i.e., the practice of making only a perfunctory or symbolic effort to do a particular thing), and (3) existing organizational structures [30]. Gender, racial, and ethnic similarities facilitate interactions with others like oneself. The similarity-attraction paradigm poses a problem for members of marginalized groups (MGs) in science in that the demographic makeup offers fewer opportunities for interactions with others like themselves based on gender, race, or ethnicity. Because underrepresentation can be even worse in positions of power in scientific organizations, network connections driven by the similarity-attraction paradigm can be less instrumental. Members of MGs are often forced instead to seek out dissimilar others to build their networks. Additionally, the presence of a small, easily identifiable group of individuals within an organization (i.e., tokenism) can result in increased performance pressures and boundary heightening for those individuals. Added pressures to perform can negatively affect performance, and unrealistic expectations can negatively impact not only perception of the individual but the group they are associated with. Recommendation algorithms in social platforms have the potential to reform or eliminate these social biases and boost science communication, but are they designed to?

Social media operate on the basis of algorithms that supposedly 'optimize' (i.e. personalize) and, thus, select communication and contacts according to the logic of consumer preferences. This logic is diametric to that of science communication. Communication via social media tends to follow the majority opinion creating 'echo chambers' while science communication is supposed to inform about new developments and stimulate critical thinking on the part of the recipient [31]. Network-based people recommendation algorithms are widely employed to suggest new connections in social media or professional platforms. While such recommendations typically enhance cohesion, the feedback loop between the algorithm and the changes in network structure may worsen social biases such as the Matthew effect of accumulated advantage (i.e., the tendency of individuals to accrue social or economic success in proportion to their initial level of popularity, friends, wealth, etc.) and polarization (i.e., the segregation within a society that emerges when factors result in the differentiation of social groups) [32]. Homophily (i.e., the tendency for people to seek out those who are similar to themselves) can put members of MGs at a disadvantage by restricting their ability to establish links with a majority group or to access novel information [33–35]. Research shows that as group size decreases, individuals in minority nodes benefit more from heterophilic interactions and are impaired by homophilic interactions. Minority nodes recover higher degrees by full in-group support when homophily increases, but they suffer from poor accessibility when it comes to dissemination of information spread by the majority [33,35]. These findings are supported by a different study in which five people recommendation algorithms were evaluated by systematically applying them over time to different synthetic networks [32]. The research group found that all algorithms, except for Node2Vec, are prone to favor and suggest nodes with high in-degree score (i.e., the number of incoming links). Furthermore, if both classes are heterophilic, recommendation algorithms can reduce visibility of members of minority groups.

These models lay the groundwork for studying how network properties can lead to biases in the ranking of nodes in social media and professional platforms. As a counter measure to these biases, increasing the connectivity of minority nodes can mitigate the "segregation effect" [32]. Studies such as these highlight the fact that more large-scale data that includes MGs should be collected. This is easier said than done, however, since sampling methods from networks can impose a bias on the representation of MGs, or hard-to-reach populations can be absent from the datasets altogether. Lack of representative data of MGs contributes to inequalities, particularly in ease of access to information. In the following paragraphs, I will discuss some well-documented strategies for career development, some additional barriers that members of MGs face in pursuing these strategies, and community measures empowered by social media that can begin to address them.

Mentorship (i.e., a relationship where a more senior, experienced individual is committed to providing developmental assistance and guidance to a less experienced protége) is invaluable. Obtaining a dynamic mentor represents the addition of a strong tie to an individual's social network that provides access to valued resources. Mentors provide mentees with career development and psychosocial support; they nominate mentees for challenging and visible assignments and provide coaching to help their mentees succeed [30]. By introducing mentees to influential individuals, mentors confer a sense of legitimacy on their mentees. Mentees have greater opportunities and higher compensation and receive more promotions than those who have not received mentoring. Mentees are also more satisfied with their jobs and careers and have greater intentions to remain in science. One barrier members of MGs face in finding mentors is that the upper echelons of scientific organizations are dominated by white males, meaning there are fewer role models (i.e., individuals sharing characteristics of identity) available to serve as mentors for members of MGs. At the same time, members of MGs in the upper echelons may bear a disproportionate burden as mentors due to the proportionately higher number of potential mentees who might seek them out.

Similar to mentor-mentee relationships, individuals engage in networking and network groups to help build developmental relationships that in turn improve their social networks by influencing the size of their networks, their pattern of ties, and the resources available through their ties. Network groups provide networking opportunities, social support, and career development for their members. They also advise senior management and human resource managers on issues that concern their members and attempt to create positive organizational change. Network groups are a means by which members of MGs can find and meet other individuals in their organization, thereby affecting the number, strength, pattern, and resources of their network ties [30]. In combination with mass media, individuals and communities that are a part of network groups can create popular awareness leading to wider public opinion and activism. This type of communication via social media can affect positive change if it is goal-oriented and calculated [36]. One example of such communication is the Twitter tag #BlackBotanistsWeek. This is a movement that began in 2020 during the COVID-19 pandemic in response to a rising need to combat systemic racism in scientific and academic institutions. Now #BlackBotanists is a growing and vibrant community that gives their followers a platform to voice and amplify their thoughts and opinions.

6. Diversity and equitability can foster innovation and improve science

Scientific progress has been built on racism in many cases (e.g., HeLa cells) and there have been systemic exclusionary practices against many social identities in universities, research institutions, and public learning environments. Yet science and learning opportunities should be for everyone. Despite this premise, it is clear that LGBTQIA + scientists, female scientists, scientists of color, and scientists with disabilities, as well as those at the intersections of these identities, continue to be under-represented, unsupported, harassed, discredited, or ignored [37,38]. In fact, the diversity-innovation paradox says that diversity fosters innovation, yet members of MGs that diversify organizations on average have less successful careers within them. A study by Ref. [39] aimed to examine this paradox by using text analysis and machine learning to follow a near-complete population of ~1.2 million US doctoral recipients from 1977 to 2015. Their analysis found that under-represented groups produce higher rates of scientific novelty, but their novel contributions are devalued or discounted. They also found that (1) novel contributions by gender and racial minorities are taken up by other scholars at lower rates than novel contributions by gender and racial majorities and (2) equally impactful contributions of gender and racial minorities are less likely to result in successful scientific careers than for majority groups [39].

Despite such findings, there is a lot of pushback against scientific workforce diversity efforts because some people in positions of power think these efforts are antithetical to meritocracy (i.e., the notion that one succeeds or fails solely on one's ability). But, diversity is not about individuals, it is about the collective. Every person has multiple, intersecting social identities, and highlighting differences in the scientific enterprise is essential to cultivating talent and accessing excellence across the social spectrum. Diversity leads to better problem-solving, grows the talent pool, and is important to long-term economic growth globally [40]. Scientists, especially policy makers and others in positions of power, should aim to increase equitable participation in science.

Equitable inclusion of scientists of different nationalities, ethnicities, socioeconomic backgrounds, academic backgrounds, and thought processes strengthens research groups. The combination of knowledge and skills from different backgrounds or research cultures helps science excel. It has been shown that the more scholars are embedded in collaboration networks, the higher the research quality [41]. In the same vein, results show that the most successful research teams have a moderate level of cultural diversity [42]. There are ways to enable diversity and inclusion in science and they include industry-backed minority and leadership training, less prescriptive hiring practices, incentivization of inclusion, and increased representation in hiring committees [43]. In light of the findings just presented, it is imperative to promote diversity in science to not only improve science and research quality, but society overall [44].

7. Integration of science communication practices into education can promote interest and engagement in science

Internet access and social media are becoming ever more important in the changing landscape of science and science communication. Internet access is unavailable or restricted in some locations and this can affect scientists and non-scientists' ability to establish an online presence, learn from others, or communicate information to demographics that may gain from it. Dr. Boykin-Okalebo encourages us to acknowledge the common Western-centric assumption that everyone has Internet access and think about who cannot engage with the conversations and resources available online. Information sharing is a pillar of education; thus, this discrepancy in accessibility hinders the impact of science and science education by limiting the sharing of information. Social science research has uncovered the inequalities in schooling experienced by MGs in the developed, and developing, world. These inequalities, such as lack of Internet access, are frequently based in socioeconomic status and this can be a barrier to effective STEM (Science, Technology, Engineering, Mathematics) teaching and learning. Learners tend to get an education of variable quality depending on their socioeconomic background [45]. Factors such as lack of study motivators and parental support, poor school administration, and lack of qualified or experienced teachers generally characterize the learning environment at underperforming schools [46]. Whilst education reform is needed at an international scale, socioeconomic status should not be an obstacle to access to scientific information or science learning.

A microcosm of socioeconomic-based inequality is exclusion from institutions like museums and science centers. These institutions are meant to be designed to encourage visitors to be inquisitive, a cycle that has the following stages: (1) a surprising phenomenon that spikes initial curiosity; (2) exploration, where the visitor further interacts with the exhibit; (3) explanation, in which the label explains the science; and (4) relevance, where the label relates the phenomenon to everyday experiences [47]. There are institutions that try to ameliorate barriers and support cross-cultural learning via virtual offerings and Internet-guided tours, such as the Smithsonian National Museum of Natural History or the Boston Museum of Science, but inclusivity should not be expected everywhere. In a study by Ref. [48]; institutional science education practices were found to be grounded in expectations about visitors' scientific knowledge, language skills, and finances that are problematic. Participants from low-income or minority groups are thus excluded from science learning by reinforcing a preexisting sense among participants that museums and science centers were not for them. However, there are broader structural features of society that should be considered when developing inclusive practices that better support cross-cultural learning opportunities.

For example, lack of Internet availability, socioeconomic status, or social biases in communication platforms can make it hard for marginalized communities to learn or access the information they need. Effective communication and translation of scientific findings into policy and practice has been slow in many countries considered low or lower middle-income. Scientific progress is also slow in these countries. This is not because the populations in these countries are disinterested in science, incapable, or resistant to change. In fact, studies have shown that young South African learners enjoy and value science more than their international peers [46]. Instead, it is because such countries have systems in place that are under-resourced and thus insufficiently responsive to the needs of the populations [49]. This is evident in a country like South Africa where teacher competence in teaching reform-based science in large classes is one of the key challenges in the continuing reform of the education system. Most schoolteachers in South Africa have little experience, meager training, and operate in large and poorly resourced science classrooms [46]. also found that 80% of public schools in South Africa have infrastructure issues and a lack of resources for practical learning, which introduces major challenges for implementation of inquiry-based teaching methods.

Social media platforms are increasingly being integrated into learning as an informal pedagogical tool; they can play a massive role in educating people on all kinds of issues. This integration fosters engagement and increases interactional competence and collaborative skills. This is especially true for a country like India that has a low literacy rate and where only 8–10% of the eligible adult population can attend formal educational institutions to pursue higher education [36]. [46] suggests increasing public engagement of STEM initiatives through outreach to attract young learners into STEM careers, a pursuit strengthened by tools like social media. It is unlikely that under-resourced schools in poor or rural areas will gain access to more resources; integration of communication practices in STEM classes represents a more immediate solution to garner greater interest and understanding of STEM disciplines and push learners to pursue careers in these disciplines. Dr. Yoshitaka Takano expounded on this and spoke about the use of social media as an educational tool to teach others complex methods, akin to JoVE, the peer-reviewed scientific video journal, and explain complex ideas in simple terms that are digestible by the public.

Students and faculty members are increasing their use of social media technologies to boost teaching and learning inside and outside the classroom. In a study focusing on the successes of second-year implementation of social media in a minority serving institution, there were positive impacts on students and grades improved significantly [50]. The following educational benefits are associated with the use of social media: (a) improved communication between students and instructors, (b) increased opportunities for networking or collaboration among students, (c) rapid resource sharing, (d) access to course materials by students after class, (e) provision of an alternative platform, and (f) exposure of students to technologies ([86]; [51]. Students' interest in academic subjects is also enhanced by social media [51]. To further stimulate and build that interest in science in these populations, there must be simple and cheap fixes for the lack of adequate facilities that handicap STEM learning. A solution to this is the development of inexpensive science models that can be used in non-laboratory settings. One example are the BioBits educational kits that were created to assist young learners to conduct biological experiments in classroom settings. It has been shown that children and young adults that use these kits experienced improved learner confidence in topics such as CRISPR-Cas9 gene editing and increased their self-identification as scientists [52].

Importing and exporting of scientific information to and from marginalized communities is crucial for deployment of real-world solutions, but implementation of that information is also crucial. Thus, barriers that impede access to or understanding of this information should be broken down, and this problem should be a concern for authoritative bodies at the institutional, governmental, and intergovernmental levels. Science and technology are essential for the survival of developed and developing nations. Amelioration of inequities in the world is unlikely, but progress could be achieved if there were a universal will to redress the current imbalance between marginalized groups and the majority.

8. Transformation of the publishing industry in the wake of open-science

Other key topics of the panel discussion centered around the for-profit publication industry, the problems associated with it and if and how open science or preprints can settle some of those problems. This question was motivated by the announcement from the U.S. government that by 2025 all taxpayer-funded research will be publicly available. At a global scale, Plan U is a proposition from scientists of many disciplines to urge funding agencies to mandate the posting of preprints by grantees. Plan U was inspired by the recognition that preprint servers such as arXiv (https://arxiv.org/) and bioRxiv (https://www.biorxiv.org/) are a successful and low-cost mechanism for providing free access to research findings. A meaningful deployment of Plan U globally would mean free access to the world's scientific output for anyone with internet access. It would also inevitably reduce hosting and archiving costs while accelerating research by allowing scientists to follow up on new experimental results sooner than they might if they had to wait for publication in a journal [53].

Dr. Jeanne Harris and Dr. Mary Williams both backed open-science/open access (OS/OA) publishing, cheaper and faster communication, and the implementation of pre-prints at more journals, as well as scientific society journals. Indeed, open research is associated with increases in citations, media attention, potential collaborators, and/or job and funding opportunities [54,55], and publishing practices of society journals are more readily influenced by authors and readers than those of for-profit publishing companies. However, others decried the 'gatekeeping' by both large and small society journals. By definition, gatekeeping is "the activity of controlling, and usually limiting, general access to something". Panelists spoke about how this manipulative behavior by journals has led to the corruption of the publication industry and how profit incentive can negatively impact scientific rigor of the peer-review process. It is no secret that scientists pay to publish their research and pay again to read others'. Additionally, we are compelled to freely volunteer our time to critique others' work without compensation. In short, the communication of research results is achieved at the expense of scientists and to the financial advantage of publishing companies.

As scientists, we must publish to succeed and this pressure to publish in an increasingly competitive environment has led to more publications annually, but it has also led to more rampant research misconduct and lower-quality science being published in predatory journals [56–59]. The scientific process depends on trust and intellectual honesty, but there may be a human temptation to be intellectually dishonest or untrustworthy to achieve career success. In an attempt to rush to publication, scientists may unethically cut corners and disregard scientific rigor [60]. This no doubt contributes to the academic publishing industry's worldwide sales amounting to more than 19 billion dollars, positioning the industry between the recording and film industries in terms of total revenue. Five publishers dominate - Elsevier, Black & Wiley, Taylor & Francis, Springer Nature, and SAGE. These publishers' high profit margins (~40%) outcompete Microsoft, Google, and Coca-Cola, with demand supported by public expenditures in the form of research grants, which budget for the costs of publication [61,62]. And despite that public investment, readers must pay for access. OA publication is a promising but costly solution. Unfortunately, big publishing companies have little incentive to simplify and reduce the costs associated with publishing to make OA more affordable. Instead, for OA they may as much as double article processing fees, or they may increase article acceptance rates to sustain profit margins (26–27% to 35–55%; [63]. The former exacerbates inequities in access to platforms for sharing scientific results, and the latter can reduce the quality of scientific research being published.

9. Mechanisms for open-science and 'how' and 'what' to share with other scientists

Dr. Sophien Kamoun expanded the discussion on flaws in the current publishing model, explaining that scientists should not judge research based on non-scientific metrics like journal impact factors. In reference to this, he highlighted the San Francisco Declaration on Research Assessment (DORA), which explicitly states that journal impact factors should not be a proxy for judging the quality and importance of a scientists' work. This and other DORA recommendations were particularly aimed at "funding agencies, academic institutions, journals, organizations that supply metrics, and individual researchers" [64]. Dr. Kamoun urged individual scientists to convince their institutions to become signatories to DORA (https://sfdora.org/sign/). He also further advocated for preprints as a driver of open science. Preprints have been shown to have many advantages: opportunities for open access and for researchers to maintain copyright to their work, wide dissemination, feedback and critical thinking, community governance, and a fast and open communication hub [65]. Dr. Kamoun and others expressed how incorporation of preprints into scientific policy and research practices could promote research integrity, open data, and reproducibility.

One of the newfound mechanisms for promotion of open data and open science is open repositories like Zenodo (https://zenodo.org/). Zenodo is a general-purpose open repository developed under the European OpenAIRE program and operated by CERN. It allows researchers to upload research papers, data sets, research software, reports, and any other research-related digital artifacts and create a digital object identifier (DOI) for each. Zenodo is becoming popular among scientists because it is safe, trusted, citable, and has useful features such as usage statistics, GitHub integration, versioning, no waiting times, and private sharing options via the restricted access mode. All data and images archived on Zenodo are published FAIR-ly (Findable, Accessible, Interoperable, and Reusable) within hours of their creation. Zenodo has been used for many small-scale and large-scale projects (e.g., Ref. [66]. I anticipate that Zenodo will become the new gold standard for open-access repositories, especially with crowd favorites such as FigShare (https://figshare.com/) potentially becoming paywalled.

While the comments on open science and science communication from the panelists focused on 'how' to share science, it is equally important to know 'what' to share. This point was raised by a member of the audience, Dr. Fumiaki Katagiri (Ph.D.), a professor in the College of Biological Sciences at the University of Minnesota and an expert in plant disease resistance. Dr. Katagiri shared what he believed should be prioritized and why, paraphrased here as follows: 1) We conduct research in highly context-dependent biological systems, and we must share a lot more information if we want to accurately compare others' results to ours. The information should include metadata and be detailed and nuanced. 2) The information we do share needs to be highly organized and searchable. An easily navigable database for something like negative results will enable others to find information efficiently and effectively. 3) We need to organize information to be computer-friendly, not just human-friendly. Computer-friendly information will reduce manpower required to maintain and update the database and potentially reduce redundancy across multiple independent laboratories. This form of organization will benefit artificial intelligence (AI), and AI can be leveraged to find associations and form hypotheses. AI could also be used to disseminate research information in the form of computer-generated podcasts, videos, and audiobooks, or even research manuscripts, freeing up more time for researchers to focus on generating results to share. Dr. Katagiri also stressed, however, that the output is only as good as the input, so the quality of the data is critical.

Resources like Research Data Management @ Harvard (https://researchdatamanagement.harvard.edu/) provide guidance and specific tools and approaches to help manage research data. Being mindful and proactive about data management, data acquisition and collection, storage, security, and analysis, and dissemination and preservation will all benefit you in your research journey. The Harvard resource recommends that before beginning your research, you ask yourself these four groups of questions to maximize research success and rigor:

> (1) How can I best manage my data throughout the lifecycle of my research to save time and money in the future?; (2) How can I acquire data in an efficient and ethical way, and how can I ensure that my data is used appropriately?; (3) What are my options for effectively organizing, storing, securing, computing, and analyzing my research data?; (4) Why is it worthwhile to share my data? What do funders and journals require? Can I get help with data curation?

These questions will assist in guiding your research through its various stages and answering these questions thoughtfully will lead to actionable plans that ease the challenges you will face.

10. The shifting perception on literature corrections

The fourth topic panelists were asked to dissect was the taboo associated with literature corrections (i.e., retractions). Our reaction to mistakes and misconduct in science is influenced by how we perceive 'the scientist,' often shaped by an ideal that a scientist is one who seeks truth through experimentation. Yet no one is devoid of human flaws, and we should not expect scientists to be devoid of flaws either. Retractions are a way to alert readers to unreliable material and other problems in the publication record. There are a series of reasons why an article would be retracted, and they include error, fraud, duplicate publication, and plagiarism. The pressure to publish in high-impact journals incentivizes fraud while disincentivizing proper scrutiny of "desirable" results or publishing of negative data. The percentage of articles retracted for fraud has increased almost 10-fold since 1975 [67]. In a detailed analysis of 2047 biomedical and life-science research articles indexed by PubMed as retracted, it was found that only 21.3% of retractions were attributable to error [67]. In contrast, 67.4% of the retractions were attributable to misconduct. It is also interesting to note that teams smaller in size have more retractions [68]. All of this information may imply that retractions are 'bad'. However, the question of whether retractions are 'good' or 'bad' does not have a simple answer.

Retracted science is often costly and erodes public perception and confidence [60]. The number of retracted scholarly articles and the rate of retractions has risen sharply in recent years [69,70]. There are two interpretations for this increase in retractions: 1) scientific integrity is in decline or 2) self-correction of science is improving [69]. A sign that self-correction is improving is that the time-to-retraction has dropped significantly since the early 2000s [71]. examined the interval between publication and retraction for 2047 retracted articles indexed in PubMed and found that time-to-retraction averaged 32.91 months. Among 714 retractions published in or before 2002, retraction required 49.82 months; in 1333 retracted articles published after 2002, retraction required 23.82 months [71]. This reflects a fundamental change in the behavior of authors and institutions. Despite what you may have heard or read, the perception around retractions has changed and it is progressing in a positive direction. The adoption of websites like Retraction Watch (http://retractionwatch.com) and the use of retractions as teaching tools have assisted in this shift of perception [72].

Dr. Morgan Carter and others spoke about how retractions should not be viewed as "bad science". Scientists are human and we make mistakes in our research. Sometimes, these mistakes make their way into the literature, not having been caught initially during the writing and editing process. Retracting a flawed manuscript and correcting it should be more widely accepted. It is far more unethical to let the mistakes remain in the publication record because those mistakes will slow progress, as other researchers get bogged down trying to replicate irreproducible results or using unreliable methods.

Even with shifting perceptions of retraction, however, there remains another challenge. Often the original versions of retracted or corrected publications remain visible and searchable; thus, visibility of retractions and corrections, and their linkage to the original articles need to be higher, so the original articles are not treated as valid content [73]. The "Reducing the Inadvertent Spread of Retracted Science: Shaping a Research and Implementation Agenda (RISRS)" project makes specific recommendations for ways in which this could be achieved [73]:

> (1) Develop a systematic cross-industry approach to ensure the public availability of consistent, standardized, interoperable, and timely information about retractions; (2) Recommend a taxonomy of retraction categories/classifications and corresponding retraction metadata that can be adopted by all stakeholders; (3) Develop best practices for coordinating the retraction process to enable timely, fair, unbiased outcomes; and (4) Educate stakeholders about pre- and post-publication stewardship, including retraction and correction of the scholarly record.

Retractions should not be taboo; if new information leads to new conclusions that undermine the original data and conclusions, there should be systems in place to fix it without the individual feeling like a failure. Error is an integral part of research science and literature corrections should be too.

11. Communication of science to the public

The fifth and final topic was about science communication to non-specialists and non-scientists. There are a lot of ways to communicate science, including traditional journalism (print and broadcast), live or face-to-face events (public lectures, debates, dialogue, museums), and online interactions (internet sites, blogs, wikis, podcasts, social media). Effective communication via these media help the public (i) recognize science as part of our real lives, (ii) see the importance of science while also being able to make decisions about it as stakeholders, policymakers, etc. and (iii) understand the threats facing our planet to better shape future political and policy decisions [74].

Unfortunately, traditional scientific career development does not typically prepare scientists to be good communicators outside academic circles or how to use social media to effectively communicate science. Dr. María Fernanda Álvarez emphasized how valuable science communication is and how we need to gear our communications specifically to our audience. For scientists, the most important aspect of their research might be how it fits into the current body of literature whereas the public wants to know how a new finding might impact their lives. Effective public engagement means figuring out ways to structure and promote conversations with the public that recognize, respect, and incorporate differences in knowledge, values, perspectives, and goals [75]. By considering the needs of the public versus scientists, an appropriate message will be crafted, and the communication will be much clearer. Similarly, advance consideration of the audience likely to be interested in study findings can result in suitable packaging and targeted communication of results. Dr. Fernanda Álvarez noted that the way one communicates with a grower could differ from the way one communicates with a policymaker. The success of a certain message or information can also depend on the experience, talent, and tact of the communicator. The price for not communicating or communicating poorly is becoming higher every day because those who are not well represented in the public arena risk losing their say, resources, or the public's trust [74].

Science communication, in the general sense of the term, is the primary link between knowledge production and knowledge consumption. Credibility and trust in the communicator are highly important in science communication, arguably even more important than in any other area of life. The credibility of science actually depends on the credibility of science communication [31]. Science communication involves expertise from multiple disciplines: subject matter scientists, to get the facts right; decision scientists, to identify the facts, so that they are not missed or buried; social and behavioral scientists, to formulate and evaluate communications, and communication practitioners, to create trusted channels among the parties [76]. To prevent erosion of trust in science, there are rules that must be followed by scientists and the public in science communication: to respect the factual truth, to not disregard the possible negative consequences of the research, to not emphasize the results more than is rightful, to not omit other options, to declare possible conflicts of interest, and to be ethical, accountable and transparent [74]. Understanding and fairly communicating risk and uncertainty are increasingly important for science and society. If the aforementioned rules are not followed, there may be an extremely problematic breakdown in communication between scientists and the public. If the communication of scientific knowledge is tainted by interests, if it is conflated with persuasive communication, if one constantly has to be suspicious of bias, this may not only create problems for decision-making but also adversely affect the scientific enterprise as a whole.

Scientific journals communicate research findings, but they may not always be accessible or digestible by scientists from other disciplines or a non-scientist. This can lead to ineffective communication and science-related misinformation influencing day-to-day decisions. To improve accessibility, journals like Nature and Science are publishing non-technical summaries and graphical abstracts of research articles. Dr. Álvarez commented on the value and potential positive impact of videos, tweets, pictures, cartoons, or drawings, noting that in addition to being accessible they can be less time consuming to prepare and publish than a formal scientific paper, alleviating time constraints as a barrier to science communication for some researchers. Other strategies for removing communication barriers that can negatively impact implementation of new practices based on research evidence include early involvement of stakeholders as research is being designed, and discussion before initiation of proposed research with those who will be affected by it [49].

Dr. Boykin Okalebo and other panelists pointed out yet another problem, the near-exclusive use of English for science communication, scientific training, and workshops, which limits accessibility. In addition to the challenges imposed on non-English speaking scientists [77,78], other problems associated with English being considered *the* language of science exist. For example, it means that scientific knowledge is often unavailable in local languages, hindering its use by field practitioners or policy makers [79], and conversely that valuable scientific contributions not published in English are often overlooked. A survey searching Google Scholar in 16 languages revealed that 35.6% of 75,513 scientific documents on biodiversity conservation published in 2014 were not in English. Ignoring non-English research can cause biases in our understanding of study systems [79].

The problems associated with near-exclusive use of English in training and workshops extend to primary and secondary education in non-English speaking countries as well. In places where English is not the mother tongue or where many languages are considered official (e.g., South Africa has 11 official languages), the use of English in science classes or on national examinations can negatively affect performance of students. This is because positive attitudes towards science from parents/guardians and their active involvement in learners' homework exercises are a key factor in learner engagement with science. Sadly, a lot of learners attending public schools in poor and/or largely immigrant communities do not get help from parents in STEM homework due to language barriers and complexity of assignments [80,81]. Researchers indicate that it can take as long as seven years for learners to master contextual proficiency in a second language [82]. For science to become truly universal, it must be communicated in as many languages as possible [83]. proposes approaches to facilitate scientists in developing countries becoming "integral members of the worldwide network of science," including specific suggestions for how to promote scientific multilingualism. If we, as individuals and members of the global scientific community, can dismantle communication and language barriers that hinder learning, sharing, and/or understanding and optimize communication with our respective audiences, we will all benefit.

12. Conclusion

The research talks were intriguing and informative while the panel discussion on science communication was incredibly enlightening and featured scientists from a variety of career stages and occupations. These are a few of the reasons I found the Japan-US Seminar in Plant Pathology to be such an inspiring conference. Future discussions akin to this one will continue to spotlight issues that affect our science and its impact and how we can address them to improve science and society as a whole.

Notes

A recording of the panel discussion is freely available to everyone free of charge on social media. It was tweeted out by the @JapanUSPlant Twitter account on September 1, 2022, but it can alternatively be found at the following website: https://vod.video.cornell.edu/media/20220831_Best%20practices%20for%20sharing%20science/1_240bsitm. If you are interested in learning more about the intersection of marginality and social media or science communication and scientific publishing in under-resourced countries, I highly recommend the following articles:

"Introduction: Marginality and Social Media" by Ref. [84]; Science communication: The link to enable enquiry-based learning in under-resourced schools" by Ref. [46]; and "Scientific publishing in developing countries: Challenges for the future" by [83].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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