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Microbial electrochemistry and technology capacity building challenges - Focus on Latin America & Caribbean and Africa

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Abstract

Microbial electrochemistry and microbial electrochemical technology (MET) is an interdisciplinary research area that has been intensively growing in the past decades. However, in some regions like Latin America & Caribbean (LA &C) and Africa, capacity building within this realm is scarce. Hence, the advancement of research and development in this field is slower and less established than in Europe, Asia Pacific or North America. This is of special concerns as MET may be important components of a biobased circular economy. Here we highlight the specific challenges researchers in LA & C and Africa have to face and put these into perspective to their general research and education environment. Subsequently, we discuss possible solutions to these challenges and showcase examples on how to overcome these. We hope that thereby awareness can be created and how each researcher in the field around the globe can individually contribute to decrease the gap in capacity building in LA & C and Africa compared to other regions.

Key words:

Bioelectrochemistry; microbial electrochemical technologies; microbial fuel cell; *Geobacter*; electrobiotechnology;

Introduction

Electrochemistry as well as microbiology are well-established disciplines, with the roots of both stretching back over centuries of scientific endeavour [1, 2]. Biological sciences and chemistry including electrochemistry, are broadly recognized as scientific disciplines of importance within the public sphere. Both disciplines are, without question, of relevance to established technologies and thus frequently offered at institutions of higher education around the world. Consequently, Faculties, Schools or Departments of Chemistry as well as Biology, in which they are embedded, are found in the vast majority of Universities that offer education in the fields of science, technology, engineering and mathematics (STEM), across the world [3].

More recently, at least from a historical perspective, is the rise of fields that combine one or more “classical” disciplines in STEM. These new fields are often denoted as interdisciplinary. For instance, bionics that combines biology and engineering, or chemical biology, that is the application of chemical analysis as well as of synthetic (small) molecules, to the investigation of biological systems. There are many more of these very recent or already established fields of research that create bridges across the broad landscape of the classical disciplines in STEM. Also gaining traction is the integration of areas beyond STEM. For example, bioeconomy needs knowledge in chemistry, biology of sustainable resources, engineering of processes as well as in economics and the legal framework [4].

These trends in research and development creates demand for adequately trained and educated researchers and engineers at all levels. When it comes to education, these newer “specializations” within STEM and adjacent disciplines are often embedded into established courses. For instance, students in chemistry can now not only choose to focus or specialize on traditional areas such as organic chemistry, inorganic chemistry or physical chemistry. They can also choose from specialisations such as biological chemistry or nano-chemistry, for example. The same holds true for biology students who, in addition to subjects like zoology, botany or microbiology, can also gain deeper education in applied fields such as biotechnology or microbial ecology. In the course of these developments dedicated M.Sc.- or M.Eng.-degrees were established to cater to the interest in interdisciplinary fields. Although students mastering these courses are without doubt equipped with the tools and skills within the respective focus area, questions remain as to whether a broader general background may be more advantageous in the long run.

Arguably, the emergence of these interdisciplinary fields can be attributed to the increasingly complex nature of global challenges, or to the increasing recognition of the value of cross-disciplinary approaches for delivering societal and economic impact, through science. Lying at the interface of microbiology and electrochemistry is a field that is rich in opportunities, as it allows to address multiple, interconnected scientific and societal challenges, including several UN development goals (directly goals 6 and 7), with the capacity to contribute to a future circular bioeconomy. This multifaceted field can be summarized under the umbrella of microbial electrochemistry and microbial electrochemical technology (MET) [5]. Microbial electrochemistry can be dated back more than a century, but the true upswing started two decades ago and since then growth in its scientific community is well evident [6].

The field has attracted researchers with a highly diverse background, ranging from molecular biology to civil engineering, leading to the emergence of different specializations. Herein lies the core challenge for the field: in order to understand and advance the microbial electrochemistry and MET broad expertise is needed that covers not just the fundamental aspects of STEM, but the competence to understand the language of different disciplines and interweave the respective knowledge from these areas [5]. Furthermore, the research and teaching require a peculiar as well as broad infrastructure that traditionally can seldom be found in one research group, one Faculty or even one University. This is compounding the challenges faced in higher education training in MET and creates challenges that require creative solutions.

Apart from these general challenges faced by all educators in the field, Latin America & Caribbean (LA & C) and Africa face additional challenges due to a number of different reasons. These are including low investment in research and development (per capita as well as in terms of percentage of the Gross Domestics Product (GDP)), slower advancement in new interdisciplinary research fields due to less investment and fewer researchers per capita as well as challenges in accessing equipment and materials, due to time-consuming importation procedures and high costs. Moreover, LA & C and Africa are huge regions with extremely diverse scenarios and the specific challenges differ from one country or even institution to another.

LA &C and Africa are gradually shifting from fossil fuels to renewable energy and clean energy and are also focusing on transitioning to a more circular economy, where the biorefinery concept becomes relevant [7–9]. Moreover, environmental problems related to the economic growth of the regions, industrialization and population growth are encouraging governments to develop more stringent environmental regulations. Developing research areas focusing on renewable energies, wastewater treatment and biorefineries is important to phase the future transition to circular economies. Due to its great potential, especially for developing economies, microbial electrochemistry and MET have fascinated researchers in LA & C and Africa. This article will provide a status quo analysis of the specific challenges for these and conclude by suggesting solutions that may help to unlock the grand capacities for higher education teaching and research in microbial electrochemistry and technology around the globe. It is worth noting that some limitations are not exclusive for this research area and also affects the advancement of research in general in these regions.

Challenges

1. **Lack of resources for research and development**

The research and development (R&D) of a country is generally evaluated based on its inputs and outputs. The commonly used measures for inputs are the degree of investment (i.e., public and private expenditure) and the human resources involved (i.e., researchers, technicians, and supporting staff). Gross domestic expenditure on Research and Development (GERD) is usually presented and discussed in terms of the country's GDP. In developed economies (i.e., USA, EU, China), R&D expenditure is generally above 2% of the GDP. This number reaches 3% in the case of the USA and exceeds 4% in the Republic of Korea [10]. Moreover, the average R&D expenditure within the Organization for Economic Cooperation and Development (OECD) member states increased by 0.2% of GDP between 2013 and 2019. In contrast, Latin America and the Caribbean region had an R&D expenditure of 0.65% of the GDP in 2013 and 0.56% in 2019. For example, GERD as reported by the Worldbank shows spending of 0.46% of GDP in Argentina, 0.29% of GDP for Colombia and 1.21% of GDP for Brazil [11]. Thus, currently in LA & C the investment in R&D is on average not only four times smaller than developed economies, but has also tended to decline over the last decade [11, 12]. For developing countries, the funding for research is mainly obtained from public sources and private investments are scarce [13]. On the contrary, in developed economies the relative share of private research funding is higher. In 2019, the participation of companies in the financing of R&D exceeds 60% in the USA, the EU and the OECD, and reaches almost 80% in China. In contrast, in LA & C the contribution of companies is around 35%, while the state government contributes 60%. This flux of financing had a direct impact on the orientation and level of research. Since LA & C allocates R&D expenditure to basic research, applied and experimental study dominates in more developed countries [11, 12]. Similarly, in South Africa the most recent National Survey of Research And Experimental Development [14], details that GERD formed only 0.61 % of GDP and is declining (from 0.62% in 2019 and 0.68% in 2018), owing to both, a decrease in business and governmental investment in this sector. However, in South Africa, a higher proportion of research funding has been directed at applied research than for basic research.

Research within microbial electrochemistry and MET requires specific equipment, materials and techniques within different areas (analytical chemistry, electrochemistry, and microbiology) for example, potentiostats, electrodes, platinum and other (noble) metals, gas and liquid chromatography. These resources are often not available in research institutes or universities, due to the scarce investment in science as explained above. Furthermore, it is challenging to maintain the precious equipment and resources in optimal condition in the ensuing years. The importation of equipment and research materials is complicated for some areas with substantial delays in receiving items, setting back research by several months or even more. Furthermore, equipment and consumables are more expensive than in other regions due to shipping expenses and importation costs. Erratic decision making on research proposals, comparable small research grant budgets and the lack of long term goals makes pro-active management often unfeasible. A typical governmental grant for a research group in LA & C is in the order of $5.000 to $40.000 per year, which is well below typical grants provided by developed countries [15]. This becomes a strong limitation for research groups starting up laboratories focusing their research in new interdisciplinary areas like microbial electrochemistry. This lack of input becomes evident when analysing the outcomes of research like scientific publications. If we compare the publications conducted in LA & C and Africa within this area, it is evident that their share in papers are extremely low compared to other regions (Figure 1). This data however does not provide insight into the number of publications per capita of researchers or in relation to GERD.

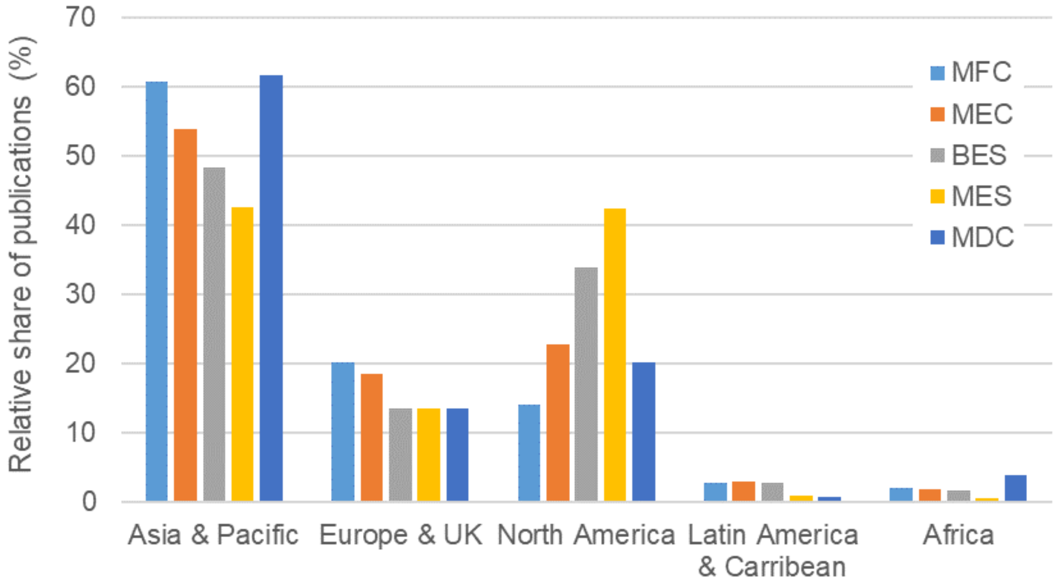

Figure 1: Relative share of the total of publications (1965 up to August 2023) per country, in the microbial electrochemistry related subjects for the different regions. Search terms used: “Microbial Fuel Cell” (MFC); “Bioelectrochemical System” (BES); “Microbial Electrolysis Cell” (MEC); “Microbial Electrosynthesis” (MES) and “Microbial Desalinization Cell” (MDC). Data obtained from Scopus bibliographic database using the function “Analyze results” choosing “Documents by country or territory”. Countries were grouped in the five regions (Asia & Pacific; Europe & UK; North America; LA & C and Africa) and relative share of the total was calculated for each region [16].

When analysing the evolution of the publications in the last decade for the countries within LA & C we see continuous growth (Figure 2). This indicates that the effort and persistence of the scientific community in the production and dissemination of knowledge has contributed to the advancement of MET.

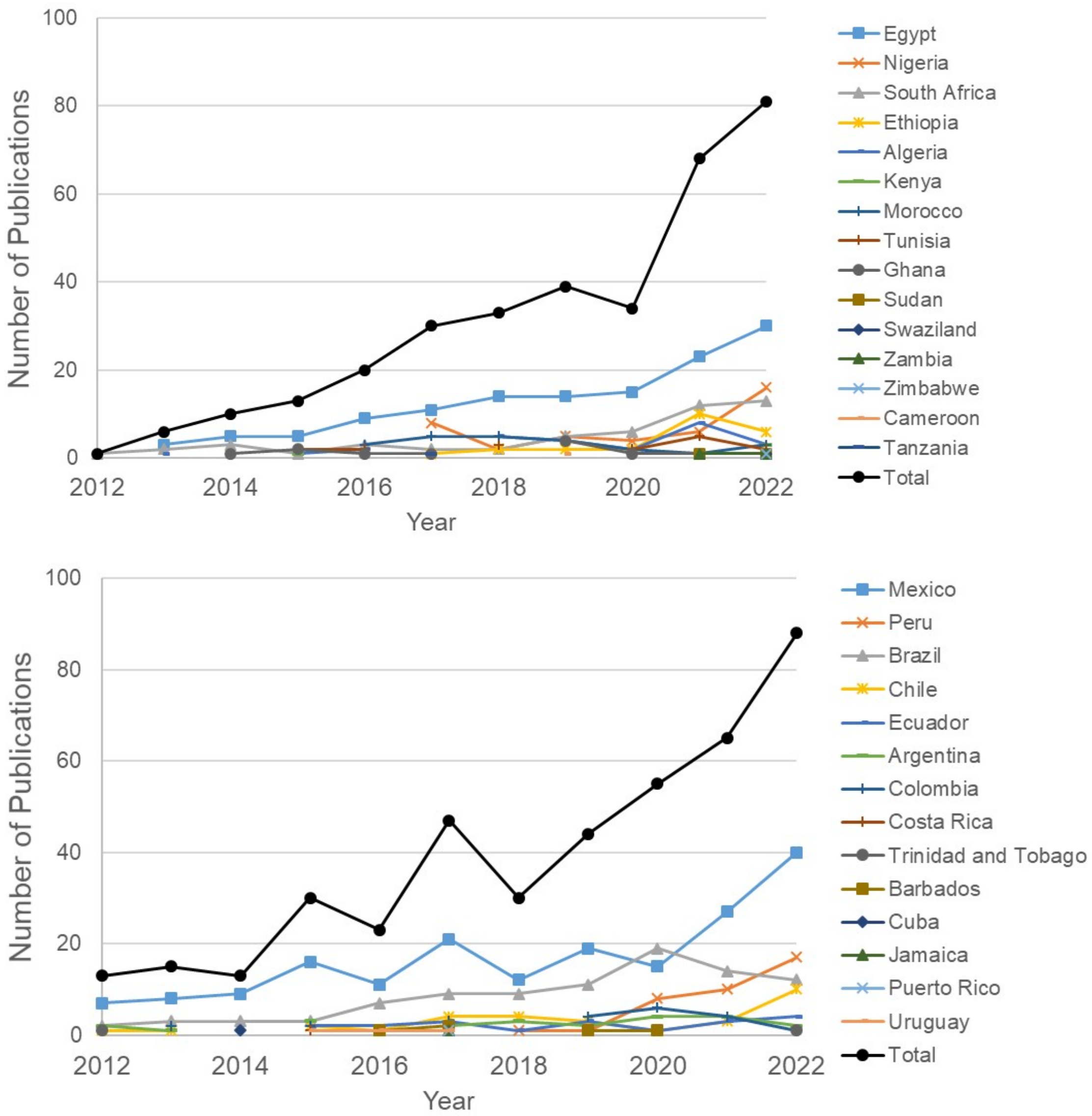

Figure 2. Publication evolution in the last decade for LA & C (a) and Africa (b). Search term used: "Microbial fuel cell". Data obtained from Scopus bibliographic database using the function "Analyze results" choosing "Documents by country or territory", African or LA & C countries were selected. [16].

2. **Lack of expertise, trained human resources and local references**

A scientific field develops by the interaction between researchers [17]. It is very important to have an active scientific community which ensures quality research and peer review processes which promotes high quality research. Human resources involved in research are an essential index to evaluate R&D capacities. LA & C has an average of 613.5 researchers per million inhabitants, Sub Saharan Africa has 97.9 researchers per million inhabitants and in Northern Africa there are 771.1 researchers per million inhabitants [18]. These numbers are among the lowest when compared to other regions of the world and even below the world average (Figure 3).

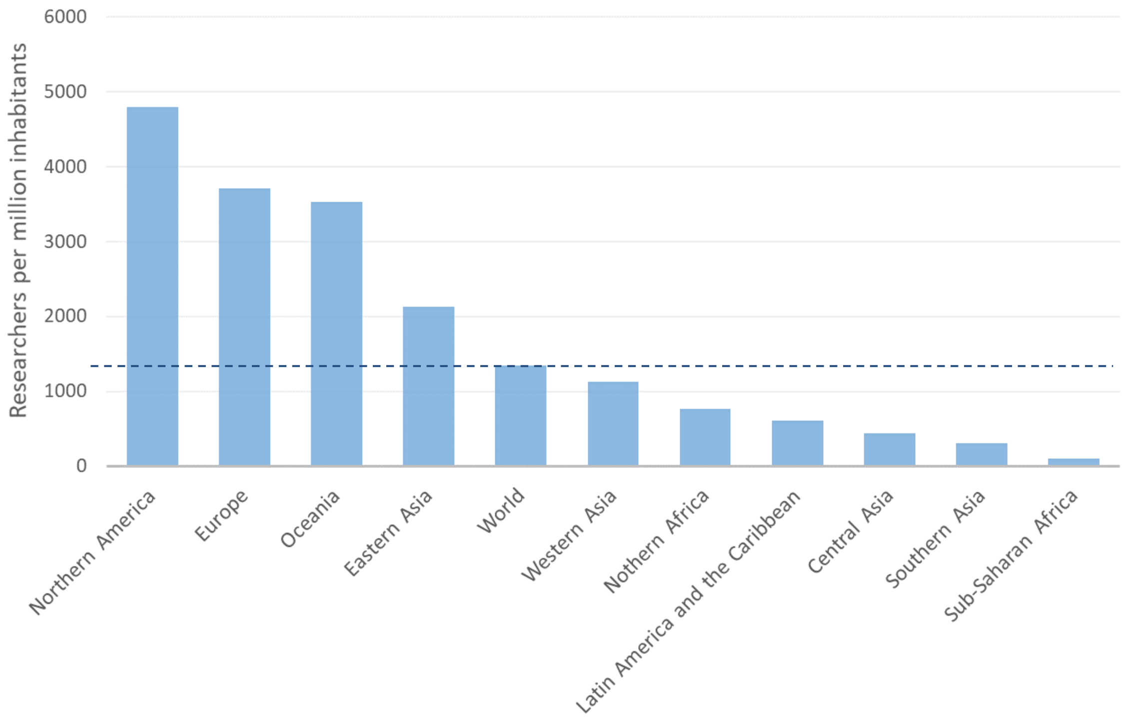

Figure 3. Researcher per million inhabitants worldwide. Data was obtained from UNESCO database the year 2021 [18].

This lack of brain power and skilled hands clearly slows R&D in these countries down. Moreover, as microbial electrochemistry and MET is a new research field, there is a need of training of researchers not exposed to the field in their own country. In countries within LA & C and Africa, where microbial electrochemistry research is performed today, the principal investigators have received the education or done a research stay (typically at the Masters, PhD, Postdoctoral level or in other research capacities) in North America or Europe in order to gain sufficient knowledge to start their own research group in their country. These interventions, notwithstanding the personal and economic costs thereof, have however allowed the establishment of an increasing number of research groups and the concomitant increase of research output in these areas in the last decade (see Figure 2). Nonetheless, the distribution of the research is not even and there are strong differences within each region. A few countries in each region are responsible for most of the publications on the specific topics (Table 1). When taking the search term "microbial fuel cell" as example, we can observe that only few countries in LA & C and Africa have managed to publish a significant amount of articles (more than 10 in the past 5 years) (Figure 4). This indicates that this research area is still underdeveloped and that there is still a lack of trained human resources in most countries. It has to be taken into account that many of the authors in these publications have double affiliations with US/ EU entities and might not reflect directly research only or mainly made in LA & C or Africa.

Table 1: Relative share of total articles within microbial electrochemistry topics per country in LA & C and Africa. Data obtained from Scopus bibliographic database [16] using the following search terms: "Microbial Fuel Cell" (MFC); "Bioelectrochemical System" (BES); "Microbial Electrolysis Cell" (MEC); "Microbial Electrosynthesis" (MES) and "Microbial Desalinization Cell" (MDC). Period: 1965 to August 2023.

	LA&C					Africa					
Country	**MFC**	**MEC**	**BES**	**MES**	**MDC**	**Country**	**MFC**	**MEC**	**BES**	**MES**	**MDC**
Mexico	42.9	62.7	47.4	11.1	25.0	**Egypt**	37.6	42.9	38.6	50.0	68.4
Brazil	20.6	10.4	18.6	33.3	50.0	**South Africa**	15.5	16.7	19.3	16.7	
Peru	8.2					**Nigeria**	12.5		7.0	16.7	5.3
Chile	7.3	9.0	14.4		25.0	**Algeria**	6.9	2.4	1.8		10.5
Argentina	5.7	7.5	11.3	55.6		**Ethiopia**	6.9	11.9	3.5	16.7	

Colombia	4.9		3.1	**Morocco**	6.9	7.1	12.3	5.3
Ecuador	3.9	9.0	3.1	**Tunisia**	4.3	7.1	7.0	5.3
Barbados	1.2			**Ghana**	3.7	4.8	1.8	5.3
Bahamas	1.0		1.0	**Kenya**	1.3	2.4	1.8	
Macao	0.8			**Cameroon**	0.8		1.8	
Belize	0.6			**Sudan**	0.8			
Puerto Rico	0.6			**Zambia**	0.8			
Uruguay	0.6		1.0	**Namibia**	0.3			
Costa Rica	0.4			**Niger**	0.3	2.4		
French Guiana	0.4			**Rwanda**	0.3			
Trinidad and Tobago	0.4	1.5		**Tanzania**	0.3			
Cuba	0.2			**Zimbabwe**	0.3			
Jamaica	0.2			**Mauritius**	0.5	2.4	5.3	
Venezuela	0.2							

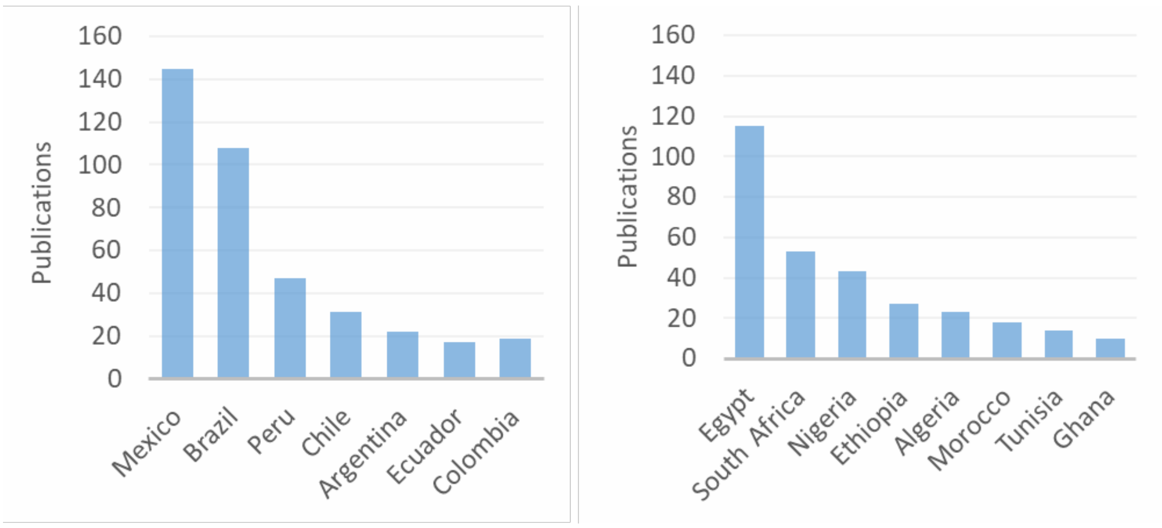

Figure 4. Number of publications per country from 2018 to 2023 in LA&C (a) and Africa (b). Data obtained from Scopus biobliographic database [16] using the search term "Microbial Fuel cell" and the function "Analyze results" choosing "Documents by country or territory", African or LA & C countries were selected. Period: 2018 to August 2023.

One problem delaying the advancement of research is the lack of local references and interaction between researchers from the different countries within LA & C and Africa. As most principal investigators or group leaders were formed in North America or Europe they have strong connections with research groups from these more active and developed regions. Additionally, most relevant scientific meetings are taking place in Europe, Asia or North America which implies high traveling costs for LA & C and African countries. Further, the base conference costs (like conference fee or accommodation) are very high for low income countries when compared to average salaries or research grants. All this translates into greater distances between researchers from the same area (Africa or LA & C) in comparison to researchers from different areas, for example, Africa with European countries. Fostering interactions between researchers within LA & C and Africa is very important. First, for sharing experiences in how research can be done in similarly constraint environments. As mentioned above, in LA & C and Africa research budgets are much lower than in other regions, so sharing knowledge on low cost materials, low cost equipment and how they perform becomes very relevant. Second, targeting common local problems. Every region has its peculiarities and experiences that are interesting for Europe or North America might not be applicable in LA & C and Africa for several reasons (economic, climate, among others). Local research is very relevant to pursue local solutions. Third, sharing experiences on cheap but efficient and qualitatively high human resource training. If the researchers in the more advanced research group within LA & C, start performing courses, or receive interns from other countries from the same region, students can get trained at a lower cost and in countries sharing the same cultural background and language (only valid for some Latin American countries).

Another interesting fact regarding researchers in this area is the lack of women representation. According to available data only for 2017 from the UNESCO Institute of Statistics, globally, 30% of the total persons employed in R&D are women [18]. This number includes full and part-time staff. Interestingly, LA & C reach 45.8%, exceeding the numbers of female participation for North America and Western Europe (32.9%) and just below the figures for Central Asia (48.5%) [12]. However, these positive aggregated numbers for LA & C should be carefully analyzed. Among countries where information is available, the most significant proportion of female researchers are in medical sciences. In contrast, the lowest ratios are in engineering and technology, and agricultural sciences, two important sectors for the community that is now represented by the International Society for Microbial Electrochemistry and Technology (ISMET). Thus, new gender balancing initiatives such as women in ISMET (WISMET) and related seminar series cannot be overestimated for boosting women's participation, also in emerging regions [19].

3. **Lack of specific university degree in microbial electrochemistry and a related non-academic job market.**

The current structure of the university curricula, which results in overspecialization, generally supports the transmission of fragmented contents from the various fields of study. In an effort to get students to learn certain contents, curricula place more emphasis on the subject itself than on how it relates to the context in which it arises. This is leading to the typical dissociation between theory and practice: What is learned in academia does not match reality or at least perception of reality. It is hard to come across any specialized topic studies in LA & C and Africa that correspond to microbial electrochemical technologies as a distinct field of study. Knowledge related to this field is still divided into compartmented contents that are presented in a fragmented and often disconnected manner. The educational challenges of teaching MET can be varied in terms of teaching methods and conceptual content. It has to include promoting understanding of its particular epistemology, enabling students to develop knowledge as well as an informed opinion to improve their conceptual understanding and to develop the skills needed to grasp them. In a compilation of twenty years of reflections on the challenges of interdisciplinary of biotechnology and chemical engineering programs, Foley [20] highlights that integrating disciplines requires both an epistemological and a pedagogical sense, especially for undergraduate programs. Indeed, the author warns about the problems that can arise if the creation of interdisciplinary degree programs is not taken carefully. This could unintentionally lead to graduates with a surface knowledge of several disciplines and lacking depth in understanding.

Companies currently working on commercializing or possessing scalable microbial electrochemical technologies are based in Europe, the USA and Asia [21]. Thus, there is not enough information about where to work or how to apply within LA & C and Africa after graduation, except for a limited number of academic researchers, mainly in universities or governmental research centres. However, there is a link to established industries in LA & C and Africa like petroleum mining sites for solving corrosion and microbial corrosion problems. Microbial corrosion of marine and piping infrastructure is an unsolved problem in the oil and gas production industry and is estimated to be 2.5 $ trillion yearly [22]. To prevent, mitigate and evaluate the damage generated by microbially induced electrochemical processes, the industry requires professionals with microbiology, electrochemistry, and engineering knowledge.

4. **Scarce teaching, instructional and training materials.**

There is a need for outreach materials for the general public, teaching materials for the undergraduate sector, and specialized textbooks to support teaching and learning in the postgraduate academic sector. Permeation of microbial electrochemical technologies into society can be achieved through outreach material aimed at the general public, and at children and young people in particular. Two concerns that future generations will have to face are energy supply and the reduction of environmental pollution; therefore, knowledge and education on these subjects is necessary. The appropriation of MET should be compatible with the different educational levels: elementary, middle and high school, as well as including the cognitive levels; i.e., knowing, understanding, applying, etc. Unfortunately, the teaching material available in electronic format is scarce and printed books and alike are even scarcer. Currently, the number of results when performing a Google search for "Microbial fuel cell" and "teaching" on the internet are 57200 in English, 2160 in Spanish, and 569 in Portuguese. Although the websites (Table 2) are oriented to children and adolescents, the texts use a language that is still too technical; moreover, very specific chemical reactions and complex diagrams can be found in these sites.

Table 2. Examples of reading material within the topic Microbial fuel cell

Link	Reference	Main content	Aimed at
https://kids.kiddle.co/Fuel_cell		Kids Encyclopaedia Facts. It explains how microbial fuel cell works.	Children
http://rd.buap.mx/ojs-dm/index.php/rdicuap/article/view/1048	[23]	This article explains in Spanish how microbial fuel cell works.	High school or university students.
https://www.ableweb.org/volumes/vol-39/?art=39	[24]	This article explains how to use Microbial Fuel Cells to teach microbiology, electrochemistry and chemistry.	High school teachers or university lecturers.
https://www.mdpi.com/2227-7102/12/6/417	[25]	This paper explains the experience of using MFC in the classroom as a tool to implement a STEM integrated curriculum.	High school teachers or university lecturers.
http://www.sciepub.com/WJCE/abstract/10327	[26]	This paper explains a series of hands-on experiments to help students understand how fuel cells work in the context of UN´s ecological sustainability goals.	High school teachers or university lecturers.

The number of book chapters specializing in bioelectrochemical technologies is only 53 out of 15851 records on "MFC", "MEC" and "BES" in Clarivate web of Science [27]. The most spread term is "MFC" with 40 book chapters out of a total of 13511 records with this keyword. In addition, 99.7 % of the documents are published in English, 0.11 % in Spanish, and 0.01 % in Portuguese, all of which means limited access to knowledge, mainly in Spanish and Portuguese-speaking regions that do not have English as a second language.

Learning of basic concepts is generally achieved through textbooks; however, since any technology has a fully applicative purpose, instructional materials, lab manuals, and handbooks are still necessary in institutions of higher education. Here the available textbooks on electrochemistry or microbiology are often excellent for the respective field, but only of limited use for our transdisciplinary field.

Another relevant issue is the access to scientific journals. Some Universities or Institutes have journal subscriptions but in less developed countries the cost to subscribe is not affordable. In the last years, the internet access and the open access journals have decreased the gap in literature access. However, internet access itself in some regions is also a problem. In particular, Africa has been reported as the region with less access to literature and the lack of institutional access was reported as incurring a great negative impact in Africa and LA & C [28]. This problem should also be taken into consideration to obtain high quality education within microbial electrochemistry, especially for postgraduate students.

Solutions:

1. Support new National policies

Despite the decreased in GERD as a percentage of GDP, increased spending for individual research areas was observed in South Africa over the period 2020-2021 [14]. This was notably for those areas informed by national policy, such as biotechnology (through the country's Bio-economy Strategy), nanotechnology (through South

Africa's National Nanotechnology Strategy), as well as environmental sciences, emphasising the role of national policies and strategies in the sciences to drive spending in the sector. The National Nanotechnology Strategy for example unlocked targeted funding from the GERD spending, helping to drive fundamental and applied research in South Africa, leading to the development of coursework and teaching at most institutions in the country, as well as the development of nanotechnology research nodes [29]. As per the last report issued in December 2022, biotechnology spending accounts for 7.9% of GERD while nanotechnology accounts for 4 % [14]. Aligning MEC research with existing policy areas, such as biotechnology may be a path to increased research funding. However, opportunities may exist to inform stakeholders and thus form new policies and funding schemes where the particular benefits of, e.g. MEC, to multiple sectors like energy security and waste treatment, may help drive new research agendas and funding for teaching modules. Driving new policy in developing countries around microbial electrochemistry and MET may help to direct targeted funding to this area. However, considering shrinking spending on GERD, more may need to be done to convince businesses to support funding in this sector as well as international funding agencies and donors. As an example, the Bill & Melinda Gates Foundation has given a grant to a research project involving microbial electrochemistry in 2011 [30].

2. Creating and empowering the core community as well as groups of interdisciplinary researchers

Two competing trends increasingly define microbial electrochemistry and MET research. One is the process of expanding and continuing specialization, which needs researchers to reach a certain level of competence in their specific field.

As more groups in LA & C and Africa gain visibility either in the scientific and/or technological applications, a growing interaction among them is expected. The writing of this article as well as other measures like the incorporation of both regions as chapters to ISMET can be milestones that show the beginning of more international interaction. This interaction shall be followed by a strong offer of workshops and other activities, encouraging the young PhD-students and postdoctoral fellows. So we hope that in the next future the organization of regional conferences as well as setting up different activities, including in person workshops at local universities, on-line lectures, conferences and clinics prepare the ground for intensive and useful practical work.

Furthermore, the Programme for Biotechnology in LA & C, United Nations University (UNU-BIOLAC) plays a critical role in promoting sustainable development by supporting education and research activities in developing countries. Through its funding for courses and other educational initiatives, the agency helps to build the capacity of local institutions to provide quality education and conduct meaningful research that can contribute to the economic, social, and environmental well-being of these countries. During the last few years, this international organization funded a series of courses involving professors and students from different Latin American countries, where bioelectrochemistry theory and practice was the main topic.

Emergence of new scientific disciplines and their subsequent subdivision into subfields are indicators of this trend. This is also the case for our field as also mentioned above. The increase in cooperation not just across disciplines but also across and beyond them is the other trend that has emerged during the past two decades, so-called multi-, inter- transdisciplinarity, depending on their level of integration and the way they approach complex problems [31]. In this context, Universities and funding agencies are starting to encourage the formation of interdisciplinary research groups. This is leading to the development of interdisciplinary work, moving from activities from isolated fields to research that involves different scientific perspectives [32].

3. Introduce microbial electrochemistry and microbial electrochemical technology as a regular course

If at all, microbial electrochemistry in most LA & C and African countries, is taught as part of chemical engineering courses at the Faculty Biology or the Faculty of Engineering. When taking the latter as example, it is usually a chapter that covers the types of electrochemical systems rather than a dedicated course that, for instance, explains the role of microorganisms in microbial electrochemistry and how to enhance their performance. For example, in Egypt, courses are tailored for engineers who will be working in corrosion control, electroplating or car batteries (Material Science course 420, Zewail City of Science and Technology) [33]. This is related to the general view that the range of jobs offered for graduates of this course which would mainly be in petroleum companies, steel industry or in battery factories. The majority of researchers and educators aiming to provide adequate teaching can be categorized to 1) those who received their M.Sc. or Ph.D. degrees from abroad or have been supervised by someone who finished their degree abroad, and 2) those who were self-taught who will learn through trial and error and who may publish low grade results or do repetitive research that may lack excellence and innovation. While the intention is good, both categories are a sporadic effort with no substantial structure or clear vision that is shared by the institution.

On a broader view bioelectrochemistry is a rich field with opportunities to introduce microbiologists, molecular biologists, physicists, engineers and chemists. It is important to expose students to a variety of examples such as galvanic and electrolytic cells, fuel cells, liquid conducting electrolytes, cell design, material science, thermodynamics, kinetics, transport [34]. This is needed in addition to teaching students about microbial diversity, extracellular electron pathways, enrichment techniques, biofilm and relevant detection techniques. Ciriminna et al [35] reports that when invigorating electrochemistry education, statements such as "electrochemistry was a complex and difficult interdisciplinary field" and that it was "hard for students" were reported. But the most important statement mentioned in the same review was the repeated need to fill in basic knowledge gaps which suggested the need to focus on educating beginners to learn the foundation of electrochemistry [35].

Although it's expected that education would be the main gateway to solving climate change and teaching students about reducing carbon emissions, decarbonization and innovations to mitigate this problem, electrochemistry education is neglected during high school education [36]. This educational stage is very important to shape the mindset of students and encourage them to choose electrochemistry for their undergraduate stage. Therefore, it is needed to broaden the interest of high school students and undergraduates who most often have the default idea that electrochemistry is corrosion and batteries only. Turner [36] suggests that we communicate to students stories about where the chemistry they are learning is coming from and where it leads to in the future. This is certainly of highest relevance for microbial electrochemistry and, given its rich past and bright future, seems highly appealing.

Updating curricula is not limited to what the students are taught, but also how they are taught and learn. Reinvigorating the curricula can be done through flipped classrooms, simulation, data analysis and laboratory experiments on different elements and levels of complexity [34]. Active learning has long been known as an effective tool that increases the performance of students in STEM [37]. Distance learning is another way that was almost forced to be applied during COVID19 pandemic [38] and could be a tool to enrich the learning process of microbial electrochemistry and MET as well as to transfer knowledge from developed to developing countries.

5. Suitable specific educational material for graduate and postgraduate courses.

Teaching, learning and training materials have different user profiles, so the formats in which teaching materials should be developed include both electronic formats and hardcopy documents.

Due to the existence of infrastructure limitations for communication and particularly for distance education in certain regions of LA & C and Africa, printed paper documents should not be left aside as an alternative for preparing didactic material.

Publishers' interest in managing the publication of textbooks depends on the popularity of the subject and the size of the market of potential readers. Both aspects seem resolved as interest in understanding microbial electrochemical phenomena and developing technologies for practical applications continues to grow with a 21% increase in the number of publications from 2019 to 2022 (data obtained from Clarivate web of Science [27]), see also Figure 2. Moreover, the size of the readership market is even larger, as researchers are joined by graduate students who need to be trained to take advantage of microbial electrochemistry and MET.

There are different textbooks available in the market with different foci, but most of them address experienced researchers (Table 3). Therefore, the preparation of a very basic online handbook, compendium, wiki or alike would be useful for young researchers who are new to the field, as well as for future industrial design and scale-up. The contents of the handbook could include lists of carbonaceous and metallic electrode materials, membrane materials and separators; lists of electroactive microorganisms and their culture conditions; lists of chemical compounds and contaminants that have been successfully employed as substrates; lists of synthesized compounds; tables of product yield ranges and energy efficiencies achieved as a function of the type of microorganism; equations for calculations in electrochemistry and biotechnology; and a section on reactor design as a function of scale of operation.

Table 3: Selection of books and textbooks for microbial electrochemistry and microbial electrochemical technologies.

Title	Editors/Authors. and publication year/Reference	Key content	DOI /ISBN
Basic Electrochemistry for Biotechnology	Harnisch, Falk, Sleutels, Tom, ter Heijne, Annemiek, Wiley-VCH, Weinheim, 2023 [39]	An introductory textbook that introduces the fundamental aspects of electrochemistry and electrochemical methods with a focus on microbial electrochemical technologies. Beautifully illustrated and with many hands-on exercises for an easy entry into laboratory work.	ISBN 978-3-527-34808-4
Advanced nanomaterials and nanocomposites for bioelectrochemical systems. A volume in Micro and Nano Technologies	Mubarak, N., Sattae, A., Mazari, S. A., Nizamuddin, S. (Eds.) Elsevier, 2023 [40]	Describes nanomaterials and nanocomposites for use in microbial fuel cells, as well as the challenges for their industrial fabrication. Explains the use of microbial fuel cells for renewable energy production.	https://doi.org/10.1016/C2020-0-03816-8 ISBN 978-0-323-90404-9
Scaling Up of Microbial Electrochemical Systems from Reality to Scalability. A volume in Advances in Green and Sustainable Chemistry.	Jadhav, D. A., Pandit, S., Gajalakshmi, S., Shah, M. P. (Eds.) Elsevier, 2022 [41]	Provides the basics of microbial bioelectrochemical technologies; illustrates various scale-up cases; discusses life cycle analysis for comparison with other technologies.	https://doi.org/10.1016/C2020-0-03641-8 ISBN 978-0-323-90765-1
Microbial electrochemical technology: sustainable platform for fuels, chemicals and remediation	Mohan, S. V., Varjani, S., & Pandey, A. (Eds.). Elsevier, 2018 [42]	Describes multiple applications of microbial electrochemical technologies. Provides novel methods for bioelectrogenesis, multi-product synthesis, and waste remediation strategies. Details various operational configurations, factors influencing reactions and integration strategies with various bioprocesses.	https://doi.org/10.1016/C2017-0-00856-X ISBN 978-0-444-64052-9
Progress and recent trends in microbial fuel cells	Kundu, P. P., & Dutta, K. 2018 [43]	Provides a discussion of the fundamentals, operating principles and applications of MFCs, for biohydrogen production and wastewater treatment. Reviews and compares MFCs with alternative energy harvesting devices. Discusses the development of membranes, electrodes, catalysts and biocatalysts. Includes commercial aspects of MFCs.	https://doi.org/10.1016/C2016-0-04695-8 ISBN 978-0-444-64017-8

Material-Microbes Interactions. Environmental Biotechnological Perspective. A volume in Developments in Applied Microbiology and Biotechnology	Aryal, N., Zhang, Y., Patil, S. A., Pant, D. Academic Press, 2023 [44]	Presents the fundamental processes of biofilm formation, the role of the material in energy exchange with microorganisms, the biofilm matrix and optimization of the biofilm formation process. Focuses on microbe-material interactions in various biotechnologies, covers a wide range of biofilm-based bioprocesses, state-of-the-art options and trends in the field. Includes photo sets on biofilm development and bioreactor systems.	https://doi.org/10.1016/C2021-0-01693-X ISBN 978-0-323-95124-1
Biological Fuel Cells: Fundamental to Applications	Rahimnejad, M. Elsevier 2023 [45]	Provides the fundamental theories and concepts of Microbial Fuel Cells (MFCs), along with the latest technologies. Presents lab-scale case studies, provides guidance on analytical methods and tools. Presents real-world applications of MFCs, performance analysis and engineering aspects. Guidance on economic and cost analysis of technologies and systems.	Paperback ISBN: 9780323857116 eBook ISBN: 9780323857123
Microbial electrochemical and fuel cells: fundamentals and applications.	Scott, K., & Yu, E. H. (Eds.). 2016 [46]	It contains the by than updated information on bioelectrical systems and their ability to drive an electrical current by mimicking bacterial interactions found in nature to produce a small amount of power.	https://doi.org/10.1016/C2014-0-01767-4 ISBN 978-1-78242-375-1

The didactic materials in electronic format allow reaching a wider audience, a faster dissemination through smart cell phones and a sustained dissemination over time without additional investment of human or monetary resources. However, the electronic format of didactic material is limited to populations with internet and electronic devices availability.

Video tutorials are, at least, showing real lab-work. Thus, we propose the creation of more video content. For instance, this is currently to some extent available in the Journal of Visualized Experiments (JOVE) for technical info and troubleshooting during experiments, and includes materials, microorganisms, assembling protocols, analytical assays, and measurements.

A total of 12 videos were retrieved in JOVE under the following disciplines: chemistry, environment, engineering and bioengineering (Table 4). However, it can be noted that:

- Only 4 of the retrieved videos were educational by covering cyclic voltammetry, electrochemical measurements, electrode potential and proton exchange membrane fuel cell. The remaining retrieved videos described specific bioelectrochemical research topics.
- There were no videos describing the biological aspect of such as phylogenetic identification, molecular biology or synthetic biology in a MET related manner.
- The videos were produced by researchers from European and American institutes so in a differently equipped laboratory environment.

This shows the clear imperative on diversifying the topics as well as viewpoints on microbial electrochemistry and MET.

Table 4: Videos available on microbial electrochemistry and MET related topics.

Title	Link	Reference
Electrochemically and Bioelectrochemically Induced Ammonium Recovery	https://www.jove.com/es/t/52405/electrochemically-and-bioelectrochemically-induced-ammonium-recovery	[47]
Waste Water Derived Electroactive Microbial Biofilms: Growth, Maintenance, and Basic Characterization	https://www.jove.com/es/v/50800/waste-water-derived-electroactive-microbial-biofilms-growth	[48]
Electrochemical Biosensing	https://www.jove.com/es/v/5796/glucose-biosensor-an-electrochemical-biosensor	[49]
Cyclic Voltammetry (CV)	https://www.jove.com/es/v/5502/cyclic-voltammetry-cv-measuring-redox-potentials-and-currents	[50]
In Situ Characterization of *Shewanella oneidensis* MR1 Biofilms by SALVI and ToF-SIMS	https://www.jove.com/es/t/55944/in-situ-characterization-shewanella-oneidensis-mr1-biofilms-salvi-tof	[51]
Hydrophobic Salt-modified Nafion for Enzyme Immobilization and Stabilization	https://www.jove.com/es/t/3949/hydrophobic-salt-modified-nafion-for-enzyme-immobilization	[52]
Electrochemical Measurements of Supported Catalysts Using a Potentiostat/Galvanostat	https://www.jove.com/es/v/5698/potentiostatgalvanostat-and-voltammetry	[53]
Standard Electrode Potentials	https://www.jove.com/es/science-education/11435/standard-electrode-potentials-direction-spontaneous-redox	[54]
Characterizing Electron Transport through Living Biofilms	https://www.jove.com/es/t/54671/characterizing-electron-transport-through-living-biofilms	[55]
Electrochemical Detection of Deuterium Kinetic Isotope Effect on Extracellular Electron Transport in *Shewanella oneidensis* MR-1	https://www.jove.com/es/t/57584/electrochemical-detection-deuterium-kinetic-isotope-effect-on	[56]
Self-standing Electrochemical Set-up to Enrich Anode-respiring Bacteria On-site	https://www.jove.com/es/t/57632/self-standing-electrochemical-set-up-to-enrich-anode-respiring	[57]
Proton Exchange Membrane Fuel Cells	https://www.jove.com/es/v/10022/proton-exchange-membrane-fuel-cells	[58]

Hands-on experience is an essential component for STEM education. It allows individuals to gain practical experience and develop the skills they need to succeed in their careers. In addition, hands-on work can help individuals to better understand complex concepts and theories by providing a tangible experience. For example, in the science involved behind the microbial fuel cells and other microbial electrochemical systems, hands-on experience is crucial to understanding how these systems work and how they can be optimized for maximum efficiency. For example, UNU-BIOLAC grants allowed the realization of workshops (Box 1), were almost half of the time available was allocated to assembling, measuring, and analysing data obtained from (mainly) microbial fuel cells, so participants were able to gain valuable experience that can be applied in their future research or professional endeavours. Overall, hands-on work is an important aspect of learning and development that should not be overlooked or better even promoted. At the same time lab courses and alike require resources, so simple and cheap but educational valuable experiments are needed. For example, this can be done by using sediment microbial fuel cells. Sediment microbial fuel cells have the advantage of the low cost of the materials necessary to build them. They can be built using a plastic container and carbon felt and the potential can be monitored with a data-logger. So, in biotechnology courses or microbiology courses it can be used to teach several concepts like respiration, biofilms, renewable energy or bioenergy and electrochemistry including even power curves. For instance they have been used in Uruguay and Argentina [59] (Figure 5). Furthermore, satellite workshops to conferences are certainly an add-on, but wet lab should be part of regular curricula.

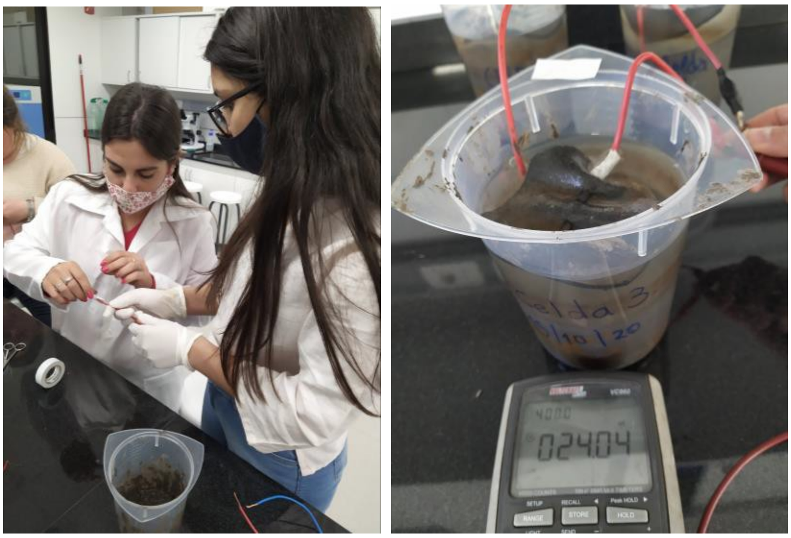

Figure 5. Students in Technological University of Uruguay building a sediment Microbial Fuel Cell in the Environmental Biotechnology Course in Water Engineering and Sustainable Development carrier.

Conclusion

We present challenges that researchers and lecturers within LA & C and Africa have to overcome in order to manage capacity building within microbial electrochemistry and MET. Clearly the research investment in these regions is lower than in developed regions like Europe, North America and some regions of Asia and the Pacific. In spite of this, in the last decades more research groups are devoting their research in this interdisciplinary area. This can be seen in the increase of papers published in microbial electrochemistry topics in the last years in some countries within LA & C and Africa. Moreover, some interesting actions have been done in order to overcome the challenges. Courses, workshops, networks, new ISMET chapters and internships within the Latin-American and Caribbean or African countries have occurred in the last years. This is clearly going to have a strong positive impact in the capacity building in microbial electrochemistry in the near future. At the same it is certainly not sufficient and more and long-lasting measures are needed to sustain and expand capacities and leverage the full potential. This is interest of both, the regions that profit from a future key technology and the field that profits from smart creative minds and skilled hands!

Box 1: Successful examples:

1. Creating global awareness

ISMET added in 2023 two new chapters: ISMET-LA and ISMET-A. This has promoted researchers from these regions to organize themselves and form networks which have had a positive impact on the human training as webinars, workshops and courses have been organized. @ISMET_LA, @ISMETAfrica

2. Regional Courses and workshops

Examples of past events include:

a. UNU-BIOLAC, Second Theoretical and Practical Workshop on Bioelectrochemistry: Bioelectrochemical Systems Towards Sustainable Wastewater Treatment, September 2023.

b. II Latin American Week of Bioelectrochemistry, Postgraduate course, June 26-30, 2023.

c. I Latin American Week of Bioelectrochemistry, Postgraduate course, June 6-10, 2022.

d. UNU-BIOLAC, Theoretical and Practical Workshop on Biosystems for Sustainable Energy Production. November 29 to December 04, 2021.

e. UNU-BIOLAC, First Theoretical and Practical Workshop on Bioelectrochemistry and Bioenergetics. December 11-15, 2017.

f. UNU-BIOLAC, Metallic Ores and Microbiology: Understanding Electrochemical Interactions to Optimize Biomining and Bioremediation Industries. October 9-13, 2017.

3. Regional networking

a) Research stays in countries within the regions. As research groups within microbial electrochemistry are more consolidated in LA & C and Africa, mobility within regions have increased in the last years. Specific scholarships of the universities or for examples from UNUBiolac are available for this (https://biolac.unu.edu/en/). PhD and Postdoc calls are also available which are important to implement electro analytical techniques and to disseminate knowledge in this area.

b) Networking. Specific funding for networking is available (for example: Proyecto REDES in Chile, Redes Cyted, bilateral funding Mexico-Uruguay) which allows researchers to visit other labs and discuss future projects and collaborations.

4. Regional conferences and networks

After the inclusion of LA & C and Africa into ISMET, both regions will be having their regional ISMET-conferences which will be an opportunity to know researchers and students and will boost even more the collaboration and the training of human resources.

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