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Condensed Matter and Materials Physics Working Group

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[1]

16.1 Introduction and Motivation

In 1956 John Bardeen, Walter Brattain, and William Bradford Shockley were awarded the Nobel Prize in Physics *for their research on semiconductors and their discovery of the transistor effect.* Their discovery is considered as a milestone in Human civilization as it opened the way to the development of the modern technology. Without the chips manufactured from semiconducting materials, one needs to imagine life without computers, communication systems, healthcare and medical devices, transportation and automotive technologies, energy generation, home appliances among others.

Humanity is now entering a new technological era marked by the quantum revolution including but not limited to quantum computing, quantum sensing and quantum encryption. *The quantum era is arriving, and it will be transformational!* [1].

Regarding its huge industrial and security impact, quantum technology has rapidly reached the realms of policymaking. A Furious international race will soon emerge to master the fundamental concepts of quantum computing and to find suitable platforms to build quantum-bits (qubits) the elementary block of a quantum computer. Recently, many countries and international organizations (such as NATO) have adopted their national quantum strategies, where a key policy objective is manufacturing quantum computers with improved error correction. To achieve this multidisciplinary objective, worldwide Condensed Matter Physics (CMP) community is devoting great efforts to study existing material candidates and predict new possible materials including two-dimensional (2D) systems, superconductors, topological materials... Beyond the realization of quantum computers, CMP community is mainly focusing on the fundamental concepts of quantum computing, quantum sensing, quantum metrology...encompassing various efforts in engineering, computer sciences, atomic-molecular and optics (AMO) and photonics.

Condensed Matter Physics is a highly interdisciplinary field of research attracting more than 46% of the Physicists in the world [2]. It aims to understand the properties of the condensed phase of matter characterized by a large number of interacting constituents, which covers solid, liquid, soft matter, optical lattices of cold atoms, classical and quantum matter, complex systems including economical, biological systems... CMP is at the basis of the modern and nano-technology and is a keystone in the development of new technological era. Based on fundamental and innovative applied research, CMP provides not only new fundamental

Physical concepts but also cutting-edge experiments to explore and control matter at different scales ranging from the atomic and nano-scale to the mesoscopic and macro-scale.

CMP is a tumultuous evolving field with a strong overlap with Materials Physics (MP), a Physics branch focusing on the synthesis, characterization and exploration of materials for applications in diverse fields as energy, biology, medicine, environment...

Beside the quantum computing race, many countries across the world are heavily investing in CMP MP, to realize on-demand semiconductors, so-called the New Oil [3], and which are required for the cutting-edge technological devices. This *Chips* race, led by the United States and China, is not limited to silicon-based semiconductors but includes emergent 2D materials and in particular graphene[1] and its heterostructures, transition metal dichalcogenides, etc.

To stay in this chips race, Europe has mounted a variety of flagship and reserach supporting programmes including the European Alliance on Semiconductors [4], the Graphene Flagship [5], Research Innovation programmes on Chemicals and advanced materials [7], European Chips Act [6], etc.

The natural question which arises at this point is about **the position of Africa in this global tech race**.

As mentioned in Ref. [8] *Africa is far behind in semiconductor technology, despite some glimmer of hope in countries such as Kenya and South Africa.* But, ironically, *many of the minerals used in semiconductor chips are indeed from Africa.* [8]

Africa is lagging behind in the global research activities in CMP and advanced materials which are intentionally designed materials with on-demand properties meeting the technological requirements of specific applications [9].

Africa needs to catch up with the worldwide tech race to avoid a further marginalization and to take advantage of its natural resources which are still exploited by non-African countries without benefits for the Continent [10].

Therefore, **fostering CMP and MP research for tech applications becomes crucial** not only for the economy development of the Continent and its sustainability but also for geopolitical challenges raised by countries heavily investing in technology.

Consequently, establishing an **African strategy for the future CMP and MP research policy** is substantially required as an evidence for Africa commitment in joining the global tech race and insuring its economical sovereignty and geopolitical security.

In this contest, the working group on CMP and MP (WG-CMP&MP) has been created within the ASFAP to come out with a **road-map for the future research plans in Africa in the area of Condensed Matter Physics and Advanced Materials**. This road-map is based on the outcomes of several open meetings and workshops with researchers from different African countries and from diaspora, and on the analysis of the received LOIs and responses to surveys. The long-term discussions involved more than 1000 (to be checked) African researchers at different career levels: Heads of research centers, stakeholders, startup founders, permanent researchers, postdoc fellows, Ph.D, Master and Bachelor students, etc.

The objectives of the present strategy can be summarized as follow

- Identifying the challenges forming the greatest barriers to promote research and innovation in CMP, Advanced Materials, quantum technologies and related topics.

[1] Graphene, known as the wonder material, is the first 2D crystal discovered in 2004 by Geim and Novoselov who have been awarded the Nobel Prize of Physics in 2010...

- Identifying the strategic areas of research in CMP and MP where Africa should invest to join the global technological race.
- Identifying the priority actions to bridge the gaps at the Educational and research levels.
- Setting a clear guideline for the future development of research and innovation in CMP and MP in Africa within a scientific and economic win-win approach.

16.2 Major challenges

Condensed Matter Physics research is critical for technological advancement and economic development globally. However, many African countries face challenges in investing adequately in CMP due to limited resources. The main challenges faced by physicists across the continent in the field of CM and MP can be categorized as follows:

- **Education**
  - Unreliable educational background

    For a successful catch-up, learning is the key for African countries considered as the 'late-latecomers' to industrialization and technology [11]. However, learning in CMP&MP with an international standard requires strong background in Physics, Mathematics, computing, and good knowledge in chemistry for students willing to pursue an experimental research career. However, in the most African countries the curricula in the Bachelor and Master levels are far below the international standard requirements [12].
  - Limited Master and Ph.D programmes

    In Africa, the majority of Bachelor students in Physics have not the opportunity to be enrolled in Master and Ph.D programmes in CM and MP. Except South Africa and certain North African countries (Algeria, Tunisia, Morocco, and Egypt), teaching Physics in several African countries is limited to basic concepts without any connection with ongoing international research activities [18]. The gender balance is also an issue. Girls are less likely to pursuit a Master or a Ph.D programmes in CM and MP as it is depicted in Fig. 16-1 showing the gender and age distributions of the participants to the survey launched by the WG-CMP&MP. All the African grouping regions have been represented in the survey as shown in Fig. 16-1(c).
  - Limited number of qualified researchers/trainers

    When African universities decide to set-up programmes in CMP&MP at the graduate levels, there may often not be qualified teachers and trainers fulfilling the international standard requirements. Several topics, including quantum information, modern computational techniques, advanced materials, etc. cannot be covered in the curricula of the majority of African universities. These topics, among others, are already included within the Master programmes running since several years in several international universities.

    Some African countries may propose training terms in international institutes for their teachers and students to perform themselves in specific topics. However, travel and visa application can

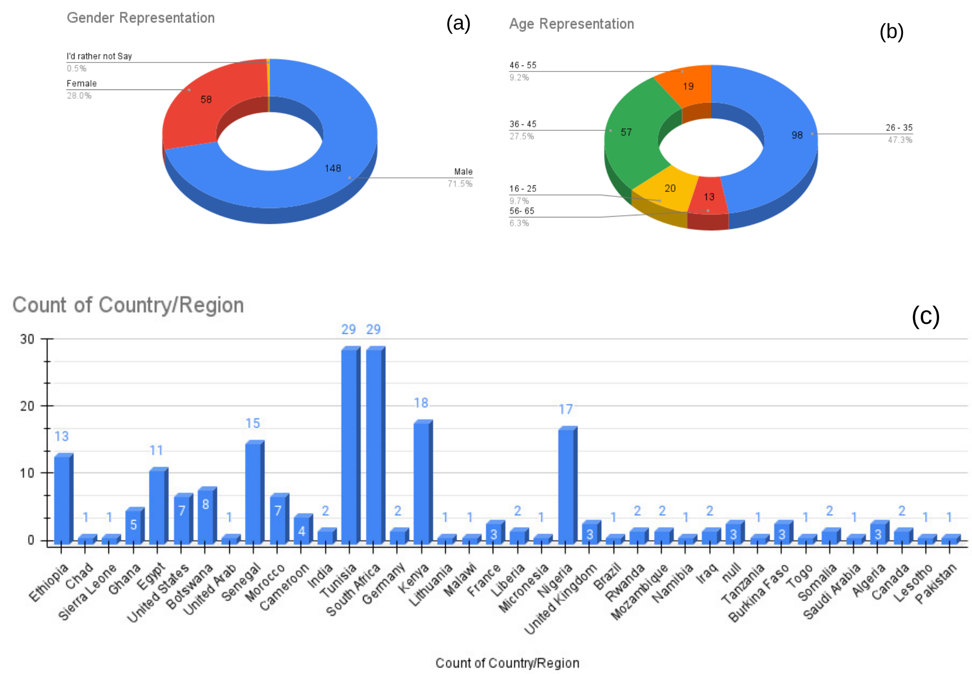


Figure 16-1. *Statistics of the online mini-workshop organized by the CM-WG. (a) The gender participation ratios. The age (b) and country (c) distributions of the attendees [19].*

be a nightmare for an African researcher and in particular students. On the other hands, it is usually difficult to raise funds to cover such visits. When grants are available, they are often not sufficient to cover the life-cost in US, Europe and Asia and researchers need to undertake endless bureaucratic procedures.

– Limited teaching equipment

Offering a successful Master and Ph.D programmes in CMP&MP requires several hands-on sessions in computation Physics, lab sessions, training in materials synthesis and characterization using research equipment etc. With the exception of South Africa, these key-stone training programmes cannot be implemented in the most of the African universities regarding the irregular power supply, the lack of computer facilities, the unsteady internet connectivity, the absence of clean rooms and the basic research equipment for Materials Science.

– Unemployed Physicists with Ph.D in CMP&MP

In most of the African countries offering Ph.D programmes in CMP&MP, the majority of the PhD holders end up unemployed. As noted in one of the submitted LOIs, *"this can be linked to a lack of innovations: most graduates nearly add no value to the companies they are employed in, regardless of whether they graduated with upper honors from the university or not. This is due to the fact that the quality of our research facilities is going low and the time taken by most university professors to offer quality research is low since the learner-teacher ratio is high" [48].*

Some of African PhD holders in CMP&MP manage to have postdoc positions in North America, China and other Asian countries but most of them may remain jobless for several years.
At the international level, there is *"a PhD factory"* in developed countries and *"supply has outstripped demand although few PhD holders end up unemployed"*. [13]. However, there rarely unemployed physicists [14, 15, 13] since if they do not manage to have a full time job in academia, they are absorbed in industry which is the largest employment base for Physics Ph.D holders. This change in career pathway is made possible since Ph.D students, in developed countries, acquire during their academic journey several skills opening the way for well-paid jobs beyond academia [15].

- Career Progression Barriers

  The primary role of lecturers in government-funded universities is teaching, leaving limited time and resources for research activities. This teaching-centric approach hampers the development of a vibrant research culture within academic institutions. Furthermore, most African countries suffer from limited or absent research positions, which creates barriers to career progression. Without recognition and support for research contributions, lecturers face challenges in advancing their academic careers and gaining international recognition.@ Btissam, could please change the paragraph and make it more specific to CM and MP?

- Brain Drain
  Most African countries allocate minimal resources to scientific research, resulting in underinvestment in CMP infrastructure, equipment, and human capital. The lack of such funding and career opportunities drives talented CMP researchers to seek employment abroad, leading to a loss of expertise and a brain drain phenomenon.

- [Sonia: more points to be added]

- **Research**

  - Challenges with existing research infrastructure

    For experimentalists in CMCMP&MP, there is a big need for synthesis and characterization facilities, including equipment for producing nanostructured materials.
    In Africa, there are a few hot spots with upgraded instrumentation as

    * **In South Africa**:
      The Centre of Excellence in Materials, Energy and Nanotechnology (CoE-MEN) is hosted by the University of the Witwatersrand (South Africa) and set-up by the African Research Universities Alliance (ARUA) Materials, Energy and Nanotechnology (CoE-MEN) - ARUA [24].
      The CSIR-hosted National Centre for Nanostructured Materials (NCNSM) focuses on the modelling, synthesis, characterisation and fabrication of new and novel nano-structured materials with specific properties National Centre for Nano-structured Materials — CSIR [25].
      NRF - iThemba Laboratory which is a national facility for pure and applied research, development and training in Accelerator based Sciences. It's Materials Research arm hosts the UNESCO-UNISA Africa Chair in Nanosciences and Nanotechnology and the 3MV Tandetron laboratory for research, modification and characterization of materials using low energy ion beams, add other centres in ZA. Home — iThemba LABS (tlabs.ac.za)
      Department of Science and Technology/Council of Mineral Technology (DST/MINTEK).

Nanotechnology Innovation Centre (NIC) which is geographically spread across the country with activities aimed at addressing national priorities highlighted by both the national nanotechnology strategy and the national research and development strategy. The Mintek NIC structure was built on the foundation of the national system of innovations (NSI) to focus on driving South Africa's transformation from a resource-based economy towards a knowledge-based economy using nanotechnology. Index (nic.ac.za)

* **In Egypt** The centres for Imaging and Microscopy and for Nanotechnology at Zewail City of Science, Technology and innovation (Egypt) [26]
* **In Morocco** The Advanced Materials Pole at the Moroccan foundation for Advanced Science, Innovation and Research (MAScIR) where research activities in the fields of materials and nanomaterials are oriented towards applied research and innovation [27].
* **In Algeria** The Research Center in Semiconductors Technology for Energetic (CRTSE) devoted to materials sciences and technology with applications in energy conversion, photovoltaic and storage, sensing, optoelectronics and photonics [28].
* **In Tunisia**: The Research and Technology Centre of Energy (CRTEn) is a R&D structure focusing on semiconductors Sciences for applications in photovoltaic cells [29].
  The centre of Research in microelectronics and nanotechnology foreseeing the synergy between Materials science and microelectronics [30].
* **Botswana**: The Botswana Institute for Technology Research and Innovation (BITRI) which hosts the Centre for Materials Science (CMS). BITRI hosts a state of the art facility for conducting research and development in mineral beneficiation, biotechology, materials science and nanotechnology. www.bitri.co.bw [Sonia: add www links for these centers]
* **Mauritius**: The Centre for Biomedical and Biomaterials Research (CBBR). It is the University of Mauritius Pole of Innovation for Health which hosts the biomaterials, drug delivery and nanotechnology units. Centre for Biomedical & Biomaterials Research (CBBR) (uom.ac.mu) [Sonia: is it related to MP? I think it is for bio not physics? Should we keep it?]
* **Uganda**: African Centre of Excellence, Centre of Materials, Product Development and Nanotechnology (MAPRONANO ACE) at Makerere University. The Center was developed out of the need to strengthen research and training in the thematic areas of materials science and engineering, nanotechnology and nanomedicine in order to develop human resource capacity in applied science engineering disciplines for the development of the great lakes region. http://www.mapronano.mak.ac.ug/
* Rwanda: East Africa Institute for Fundamental Research (EAIFR) which is a partner institute of the Abdus Salam International Centre for Theoretical Physics (ICTP) and it is also a Category 2 UNESCO institute. The institute is located at the University of Rwanda. Its main areas of research and teaching include Condensed Matter Phyiscs, Physics of the Solid Earth, High Energy, Cosmology and Astroparticle Physics. About Us — EAIFR (ictp.it)
* need centers in Cameroon: Centre of Atomic Molecular Physics and Quantum Optics (CEPAMOQ) at the University of Douala, Cameroon. [Sonia: it is better to remove this center, not related to MP]
* Ethiopia: in connection with the Table on publications
* The African Materials Research Society (AMRS) [49] was launched on 2002 to establish and straighten collaboration between the USA and Africa to promote the materials research capacity in Africa. MRS is organizing a biennial international Conference in different African countries to bring together scientists, industry researchers and Government representatives from the USA and 15 African countries. One of the main objective of AMRS is to promote collaboration between US and African countries to offer African researchers the opportunity to be in international networks and use the facilities of the MRS [50] .

However, the available equipment, in the most African countries, is old or defective, regarding the shortage of trained technicians. Getting dysfunctional equipment fixed is often unduly cumbersome and bureaucratic. Furthermore, African laboratories cannot afford upgraded instrumentation due to a lack of funds [18].

For theorists using computational techniques, the main challenge is finding computational facilities as high performance computers (HPC) or at least powerful workstations, to perform computationally intensive calculations. Such facilities are not available in the most of African countries. On the other hand, many numerical calculations need to be operated with commercial codes which are not affordable to many research laboratories. To use such codes, researchers need also to be enrolled in training programmes and workshops to keep being updated related computing techniques. However, African researchers are mostly left to their own resources and backgrounds, which is at the origin of the large gap between the research outcomes in computational Physics of African labs and other international research institutes.

There are a few attempts to boost computational Physics in Africa.

* HPC facilities are provided to researchers in South Africa [31], Egypt [32], Algeria [33]. The National Center for Scientific and Technical Research (CNRST) provides the Moroccan scientists with a remote-access to HPC [34].[Sonia: add other countries...]
* The annual African School on Electronic Structure Methods and Applications (ASESMA), organized by ICTP, offer the young African researchers an introduction to the computational electronic band structure and other atomistic simulation methods[20, 21, 22]

Figure 16-2 clearly shows the huge lack in equipment for African researchers in experimental and theoretical CMCMP&MP.

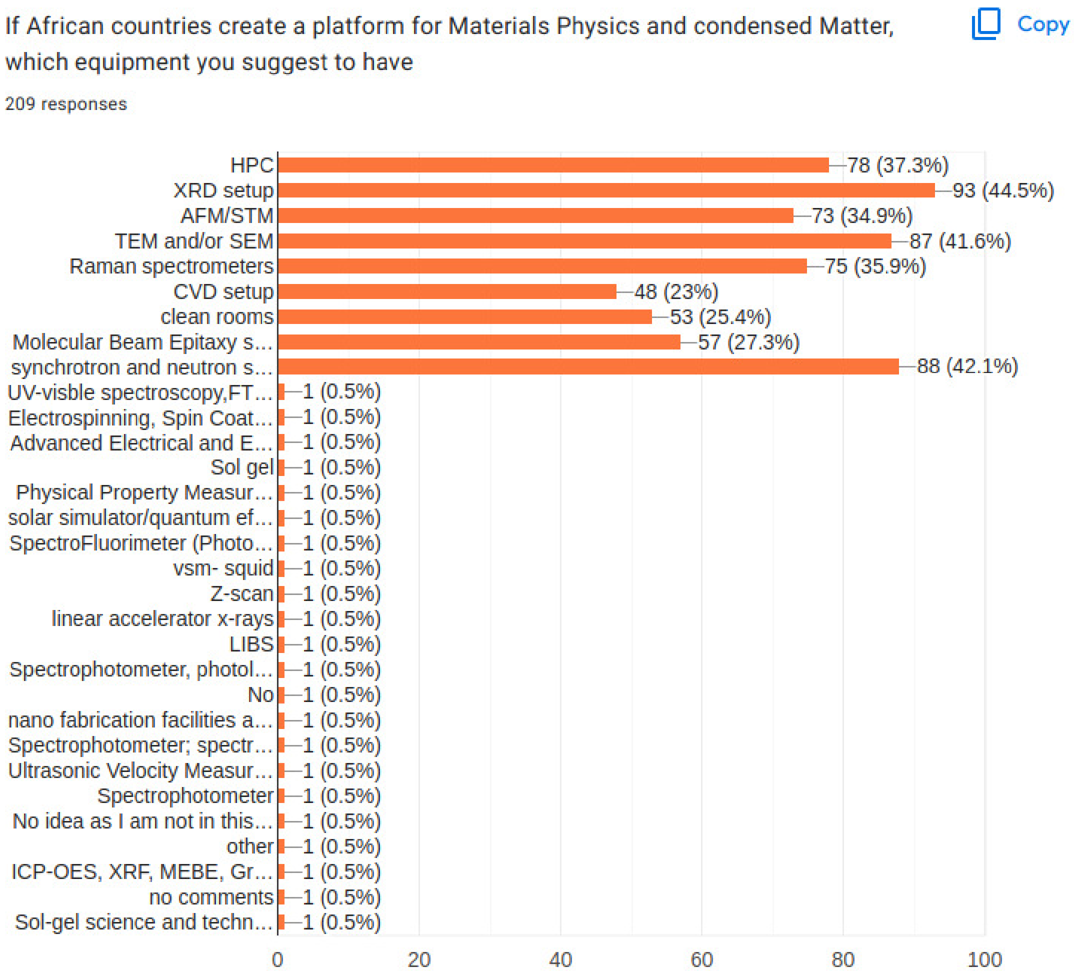
– Challenges with communication and dissemination

* Participation to international research events

  Taking part to international events is a key ingredient in the development of the research activities. There are plenty of scientific events in CMCMP&MP during the year in different countries all over the world, where outstanding researchers are invited, including Nobel prize laureates. These events offer the opportunity for African scientists to be in touch with the ongoing international research activities, to discuss their results, build-up networks, establish collaborations etc. However, access to such events is generally not possible for African researchers for many reasons

  1. Due to the lack of funds in their home institutes and their low incomes, African attendees cannot afford to cover the conference registration fees (which are usually around 500 Euros).
  2. Visas issues often plague African participation to international events even if the funds are available [18].
  3. Many African researchers are isolated from the international networks and they do not receive event announcements, in addition to problems with internet connectivity.
  4. [Sonia: add other points]

* Research paper publication



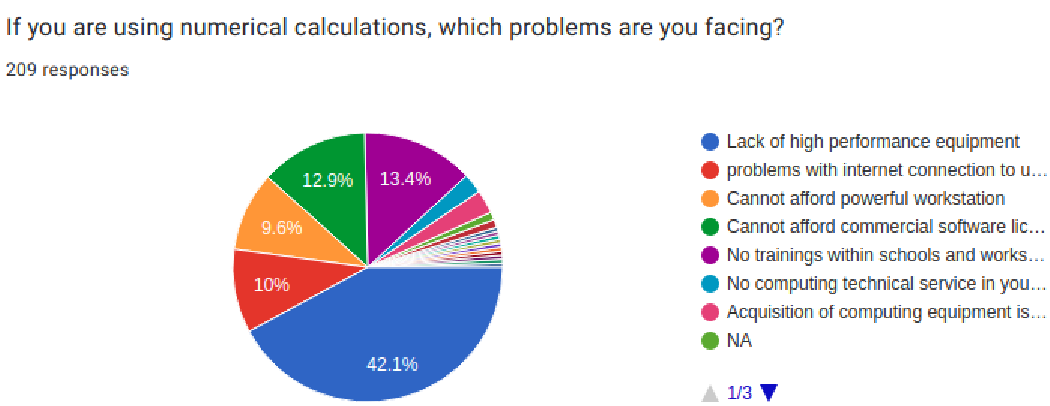


Figure 16-2. *Survey responses concerning the equipment needed for experimentalists (top) and theorists (bottom) working in CMCMP&MP. [19].*

Publishing the research results in outstanding scientific journals opens the way to researchers to be recognized at the international level and to be part of the global networks. In CM-CMP&MP there is broad panoply of outstanding journals, but many of them reject preprints from African labs because the obtained results do not meet the journal standards. Let us put bias aside and look for the reasons of the rejection.
Regarding their poor infrastructure, African researcher cannot obtain results competing with those of their peers in other international institutions. On the other hand, they do not often have access to the data base nor to published papers. Most of the African institution libraries are not subscribed into international journal publishers which require unaffordable registration fees.
Recently, many journals in MCMP&MP converted, fully or partially, to the open access scheme, which allows African researchers, among others, to have access to the published papers. However, the downside of the open access journals is the high publication charges (around few thousands dollars per paper) which cannot be covered by African labs. Some international institutions offer a free access to many journals for researchers from low-income countries. In particular the American Physical Society (APS) [35] and ICTP within its eJournals Delivery Service [36]. Nevertheless, the access to is limited to a few researchers due to problem with information access,
As shown in Table 16-1, the African countries with high publication rates in Materials science and nanotechnology are those granted with a good infrastructure as discussed in the previous section. [Sonia: add figures, statistics on number of African published papers in APS journals for example]

Country	Worldwide Rank
Egypt	31
South Africa	41
Algeria	47
Tunisia	49
Morocco	54
Nigeria	62
Ethiopia	75
Cameroon	89
Senegal	107

Country	Worldwide Rank
Egypt	33
South Africa	45
Tunisia	55
Algeria	56
Ethiopia	62
Morocco	64
Nigeria	68
Ghana	86
Cameroon	93

Table 16-1. *Publication country ranking in Materials Science (left) and nanoscience and nanotechnology (right) during the period 1996-2022, after Scimago classification [23]*

In figures 16-5, 16-6, 16-7 (see Appendix) we depicted the publication records, during the lats two decades, of different African countries categorized by regions. The last panel shows a comparison between two Africa countries with the highest African records (South Africa and Egypt) and some other countries in the world with a comparable. This figure clearly shows that, despite its huge natural and human resources, Africa is lagging behind the rest of the world in terms of research in CM&MP, which explain why Africa is far behind in technology and industrialization.

It is worth to note that despite the large community of African researchers working in CM&MP, there are only four classified journals in the field and are low-ranked as shown in Fig. 16-3.

@Samuel, we need data on the number of researchers in MP in Africa, any info from African MRS?

	Title	Type	↓ SJR	H index	Total Docs. (2022)	Total Docs. (3years)	Total Refs. (2022)	Total Cites (3years)	Citable Docs. (3years)	Cites / Doc. (2years)	Ref. / Doc. (2022)
1	Journal of Nanotechnology	journal	0.577 Q2	39	25	55	2070	253	51	4.07	82.80
2	International Journal of Polymer Science	journal	0.411 Q2	50	56	276	3367	909	269	3.29	60.13
3	Advances in Tribology	journal	0.368 Q3	22	0	13	0	39	13	2.82	0.00
4	Journal of the Southern African Institute of Mining and Metallurgy	journal	0.242 Q3	43	73	289	2348	244	272	0.75	32.16

Figure 16-3. *African journals on Materials Sciences with WOS classification [23].*

- Challenges with international collaborations

  Being a partner in an international research project breaks the scientific isolation of African countries and facilitate substantially their cross-border activities. There are several joint programmes boosting the participation of African countries in international consortia. In particular, EU proposes several collaboration schemes [37, 38, 39] as Euraxess Africa [40], Horizon-Europe [41], etc. Within such collaboration, many African students can have the opportunity to carry out internship in international labs.
  Since international consortia brings together countries with complementary expertise, the African members need to bring a relevant contribution to the research activities of the consortium within a win-win approach. With the exception of South Africa and some North African countries, the participation of Africa to international projects is very limited. This is, basically, due to the unbalance between the international and African infrastructures and research outcomes, the lack of information on available collaborating opportunities, the absence of administrative structure for the project management in the African institutions etc.

- Challenges with limited budgets

  As noted in Ref. [42] African countries are spending less than 1% of its gross domestic product (GDP) on research despite the increase in the number of scientists in the past five years. South Africa and Egypt allocate the highest budgets for scientific research which are respectively 0.83% and 0.72% of their GDP [42].
  Setting-up a research lab in CM&MP requires investment in high performance equipment as those indicated in Table 16-2. Regarding their limited budget, most of the African institutes cannot manage to get one of these facilities.
  In international labs, experimental research in CM&MP involve many Postdocs, Ph.D and Master students, in addition to trained technicians for machine maintenance. This is not the case of the majority of African labs due to the lack of funds which prevent the recruitment of students and postdocs, pushing Ph.D holders to unemployment. It is worth to stress that the stipend of Ph.D student in Africa is in general much lower than the minimum wage.

Equipment	Price (in $)
Lithography System	220 million – 500 million
Scanning electron microscopes	70,000 to 1,000,000
Transmission Electron Microscopes (TEM)	100,000 to 10,000,000
Molecular beam epitaxy (MBE)	minimum 1,000,000
Physical Property Measurement System (PPMS)	100,000 to 10,000,000 (to check
put other machines...	? to ?
Clean room (per square metre)	1,500 to 6,000

Table 16-2. *Average price range of some equipment used in CM&MP [44, 43]*

[Sonia: add more points and be more specific with CM and MP] communication, dissemination, background, financial

16.3 High-priority future needs [Sonia: or Roadmap]

The current landscape of CMP research in Africa reveals a significant gap in infrastructure, funding, and human capital. While some individual research efforts exist, the **absence of coordinated initiatives** limits the impact and scalability of these endeavors. Furthermore, the lack of state-of-the-art equipment and facilities hampers research progress and inhibits collaboration. Thus, to enhance the continent's scientific capabilities and address pressing societal challenges, some high-priority future needs for an African strategy, focusing on maximizing impact with limited resources, are identified as follows:

1. Education and capacity building

   Catching the tech race requires an immediate investment in Education which should not be limited to teaching but should also include continuous training for teachers and researchers. There is an urge to improve the curricula of CM&MP taught at different levels: Bachelor, Master and doctorate. Based on the received LOIs and the outcomes of different meetings with African researchers in CM&MP, we propose to reshape the teaching of CM&MP in Africa as follows:

   (a) Start teaching of CM&MP at the Bachelor level to raise the awareness of students about the technological impacts of Condensed Matter Physics. The curricula should include an introduction to solid states physics with lab and computation hands-on sessions. A teaching by project approach is strongly recommended with input from industry.

   (b) Build up **Pan African Master and related Ph.D programmes** an with exchange student program. The Master should involve African and International universities to insure training of African teachers and students. The African countries involved in such hub should be able to handle visa issues to facilitate the exchange of staff and students. Each Master programme could have a nodal point in an African country with a suitable teaching/research infrastructure. The teaching will focus on the fundamental and applied aspects of CM&MP as required by the participants to the survey launched by the ASFAP CM&MP working group (see figure 16-4). The proposed Master programmes are in following areas

   - **Master in Theoretical & computational CM:** with a strong focus on the fundamental aspects of solid states Physics, quantum matter and the related computational methods, including machine learning, AI and quantum computing. The students will be able to combine

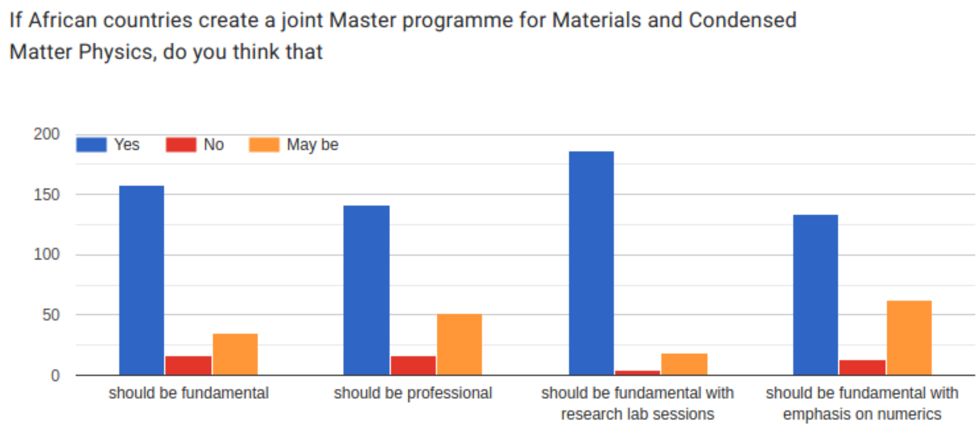


Figure 16-4. *Survey responses concerning their preferences about the nature of a possible joint African Master programme in CMCMP&MP. [19].*

numerical and analytical skills to undertake Ph.D projects in advanced CM topics including but not limited to advanced materials and quantum information. This Master programme will lay on the existence of HPC infrastructure or at least powerful workstation to carry out numerical calculations. The teaching will be based on workshops and seminars organized with ICTP and other international research institutes. A pre-master year could be planned to students with major gaps in relevant background.
After getting their Master degree, students should also be able to carry out a career in data science or quantum computing.

- **Master in Experimental and applied CM&MP:** devoted to the fundamentals of experimental CM&MP and the technological applications. This is a key Master programme for the promotion of research in CM&MP. The students will learn the different techniques of synthesis, characterization of advanced materials and the methods to control their properties. The teaching should be mostly based (80%) on lab-courses carried out in research centers or labs with suitable equipment. The students will be able to master the key experimental methods to undertake Ph.D projects in experimental CM&MP or in R&D focusing on applied MP. After getting their Master degree, students should also be able to carry out a career in industry.
- **Professional Master degree in Materials Physics and applications:** with a focus on energy, water purification, food agriculture etc The students will also be trained on entrepreneurship within startups and technology business incubators to help them setting-up their own Materials Physics based-business.
- **Master in quantum technologies:** This Master is already implemented in many international institutes. It will be an interface between three pathways: physics, engineering and mathematics where students from different paths can interact within multidisciplinary research projects and workshops. The topics include Quantum Computing, Quantum Sensing, Quantum Simulation, Quantum Materials and Quantum Cryptography with advanced practical training on quantum computing platforms, photonic quantum computers etc. The details of the Master curricula could be discussed within an African strategy for Quantum technologies.

The Pan African University Institute for Basic Sciences, technology and Innovation (PAUSTI) can be the engine to boost such joint education programmes in Africa [52, 51]. PAUSTI mission focuses on forming leaders and innovators in the fields of Mathematics, Molecular Biology and Biotechnology; Civil Engineering; Mechanical Engineering; Mechatronic Engineering and Electrical Engineering.

@Btissam and Samuel: any other idea for this section?

(c) Set-up an **International Centre for Experimental in Africa (ICEPA)** with a focus on CM&MP. *"This is an educational centre for the training of young African students, postdocs and junior faculty members in instrumentation for fundamental and applied experimental physics. The educational programme foreseen would be equivalent to a Master curriculum at a university. Many African universities do not have the necessary number of experimental facilities and instruments at their disposal for training in experimental techniques and tools.The concept of the proposed centre (named provisionally ICEPA in the following) has been inspired by the successful AIMS centres for mathematical sciences and ICTP for theoretical physics. But for ICEPA the focus is on experimental physics, strongly oriented towards instrumentation. The attachment to or at least a very close link to a university or to an existing research centre will be necessary to train and recruit qualified staff for the supervision of the experiments and to be able to issue an international recognised diploma" [47].*

(d) Strengthen the teaching activities at the Master and Ph.D levels by organizing regular schools in specific on-demand topics as computational CM&MP, quantum matter, 2D materials, quantum information etc. *"The Case of the African School for Electronic Structure Methods and Applications (ASESMA) shown that it is possible to build a network across sub-Saharan Africa with world-class research with world-class research with a relatively low budget." [21]*

2. Research

Research on MP in African is generally limited to local natural materials and their applications in particular area like construction, food, biology. To bridge the technological gap between Africa and At the international level, the key research areas in CM&MP are, but not limited to, 2D and advanced Materials for chips technologies, quan....

- Enhance existing and establish new collaborative networks between universities, research institutions, and industries within and outside Africa. These networks facilitate knowledge exchange, joint research projects, and technology transfer.
- Encourage public-private partnerships to provide funding, industry expertise, and market access, fostering innovation and entrepreneurship in CMP.
- Upgrade existing research infrastructure and establish new facilities equipped with state-of-the-art instruments as well as facilitate access to advanced experimental and computational tools.
- Invest in training programs, mentorships, workshops, and international collaborations to enhance the capacity of African researchers in CMP.
- Develop comprehensive and interdisciplinary curricula tailored to CMP by integrating theoretical knowledge with practical skills.
- Invest and fund advanced laboratories, research grants, and scholarships to attract and retain top talent. This funding should support both basic and applied research, as well as capacity-building activities.
- Create dedicated research positions for CMP researchers within universities and research centers to provide sufficient time, resources, and institutional support for conducting impactful research without compromising teaching responsibilities.

- Promote a culture of research excellence by incentivizing and rewarding research contributions. This includes recognizing research outputs in performance evaluations, providing research-related training and mentorship.
- (others...)

[Sonia: I think that, in this part, we should give detailed roadmap. I propose the following points which can be combined with those written above by Btissam]

[Sonia: we can propose roadmap for Education, then reserach....]

1. set-up research centers of excellence
    - semiconductors materials for chips: from fundamental to commercialization
    - 2D materials : graphene-like materials, MXenes, quantum dot...
    - Quantum hardware for quantum computing: superconductor-based qu-bits, and
    - Materials for energy
2. mount flagships in semi-conductors, 2D materials, quantum computing
3. (others...)

– text from Refs

16.4 Synergies with neighbouring fields

Condensed Matter and Materials Physics exhibit numerous synergies with neighboring fields, fostering interdisciplinary collaboration and driving scientific innovation across various domains.

This can be illustrated through their intersection with Photonics and Optoelectronics in studying the interaction of light with condensed matter systems and the development of optical and optoelectronic devices [45]. CMP techniques, such as spectroscopy, nonlinear optics, and photonic crystal engineering, are used to investigate the optical properties of materials and design photonic devices, such as lasers, LEDs, and photodetectors, for communication, sensing, and imaging applications. Conversely, advances in Photonics and Optoelectronics contribute to CMP research by providing tools and techniques for manipulating light-matter interactions and harnessing optical phenomena for controlling and manipulating condensed matter systems at the nanoscale.

Besides, CMP relies on light sources, such as synchrotrons and free-electron lasers, for spectroscopy and imaging experiments [46]. These techniques provide valuable insights into the electronic and structural properties of materials at the atomic scale. Advances in light sources technology, such as high-brightness beams and ultrafast lasers, enable CMP researchers to study dynamic processes in condensed matter systems with unprecedented resolution and sensitivity. Furthermore, light sources offer a wide range of characterization techniques, including X-ray diffraction, X-ray absorption spectroscopy, and photoelectron spectroscopy, which are essential for studying the properties of materials in CMP. These techniques provide information about the crystal structure, chemical composition, and electronic structure of materials, facilitating the design and optimization of new materials for specific applications.

Biophysics also intersects with CMP in studying the physical principles underlying biological systems' structure, function, and behavior. CMP techniques, such as X-ray crystallography, spectroscopy, and microscopy, are used to investigate biomolecular structures, protein folding dynamics, and cellular processes. Understanding the physical mechanisms governing biological systems' behavior has implications for biomedical research, drug discovery, and biotechnological applications. Conversely, insights from biophysics inspire CMP research, leading to the development of biomimetic materials and devices that mimic biological systems' functionalities and properties.

On the other hand, Materials physics and Particle Physics researchers often share theoretical and experimental techniques. Concepts from Particle Physics, such as symmetry breaking, gauge theories, and renormalization, have found applications in CMP research, while techniques from CMP, such as effective field theory and renormalization group methods, have been adopted in Particle Physics to study strong and weak interactions.

Furthermore, collaboration between CMP and Condensed Matter Chemistry researchers enables a deeper understanding of chemical processes at the molecular level and the development of innovative materials with tailored functionalities.

16.5 Environmental and societal impact

Condensed Matter and Materials Physics is part of our everyday life as it plays a crucial role to describe matter. Therefore, improved education in CMMP of the current and future generation will help to have a more scientifically inclined and open minded society. This will help to ensure that Africa is well positioned to have a critical mass of physicists with the knowledge, skills, creativity and versatility to face any challenge. Due to the fact that CMMP embraces various fields, it instils interdisciplinarity in the mindsets of Scientists.

16.6 Conclusion and perspectives

In the past, availability of land, raw materials and labour were considered to be important economic factors for African development while the pursuit for scientific information and knowledge were less considered. This was primarily due to inward looking and short term thinking focused on tangible things in the short term without thinking about how the search for new scientific knowledge could change the future of Africa to move away from set ways of doing things. The late Professor John Desmond Bernal, a British Physicist in his book "Science in History" stated that "It is now evident that the real source of wealth of a nation lies no longer in the raw materials, the labour force or machinery, but in having a scientific, educational and technological base, education has become the real wealth of the new age". As a result of limited investment in scientific research by most African countries with almost all of them falling short of reaching the set minimum of investing 0.5Physics is a foundational pillar for development of basic science and technology. Therefore, for Africa to advance to go beyond just catching up on the global scientific and technological race, it is necessary to fully integrate physics in the education system of Africa. In the context of our report that focuses on condensed matter and materials physics, it is critical that continental initiatives embrace its potential. For example, the African Union's Agenda 2063 "The Africa we want" which is Africa's blue print and master plan for transforming Africa into the global powerhouse of the future. For this to be fully realized, it is essential that continental science, technology and innovation policies are tailored to create an enabling environment for the successful harnessing of the immense potential that lies in condensed matter and materials physics. This cuts across a move towards elimination of limitations to access to education, access to equipment for research and fostering a strong relationship within the triple helix context. The need for advanced tools (experimental, computational and theoretical) to probe the structure and properties of materials is critical for the significant advancement of condensed matter and materials physics in Africa hence the need for significant investment and training. It should also be noted that having a improved understanding of the value of seeking answers for scientific questions, the link between theoretical and experimental research and their impact on current and future technological applications will contribute significantly to socioeconomic development of Africa. However, for this to be realized, the value of condensed matter and materials physics should be appreciated at the highest level of African governments hence the compilation of the African Strategy for Fundamental and Applied Physics. Africa is the future of the world because of the abundance of natural resources and having a significant percentage of a young population but it needs to speed up its approach to scientific thinking in order to capitalize on its advantages.

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Appendix

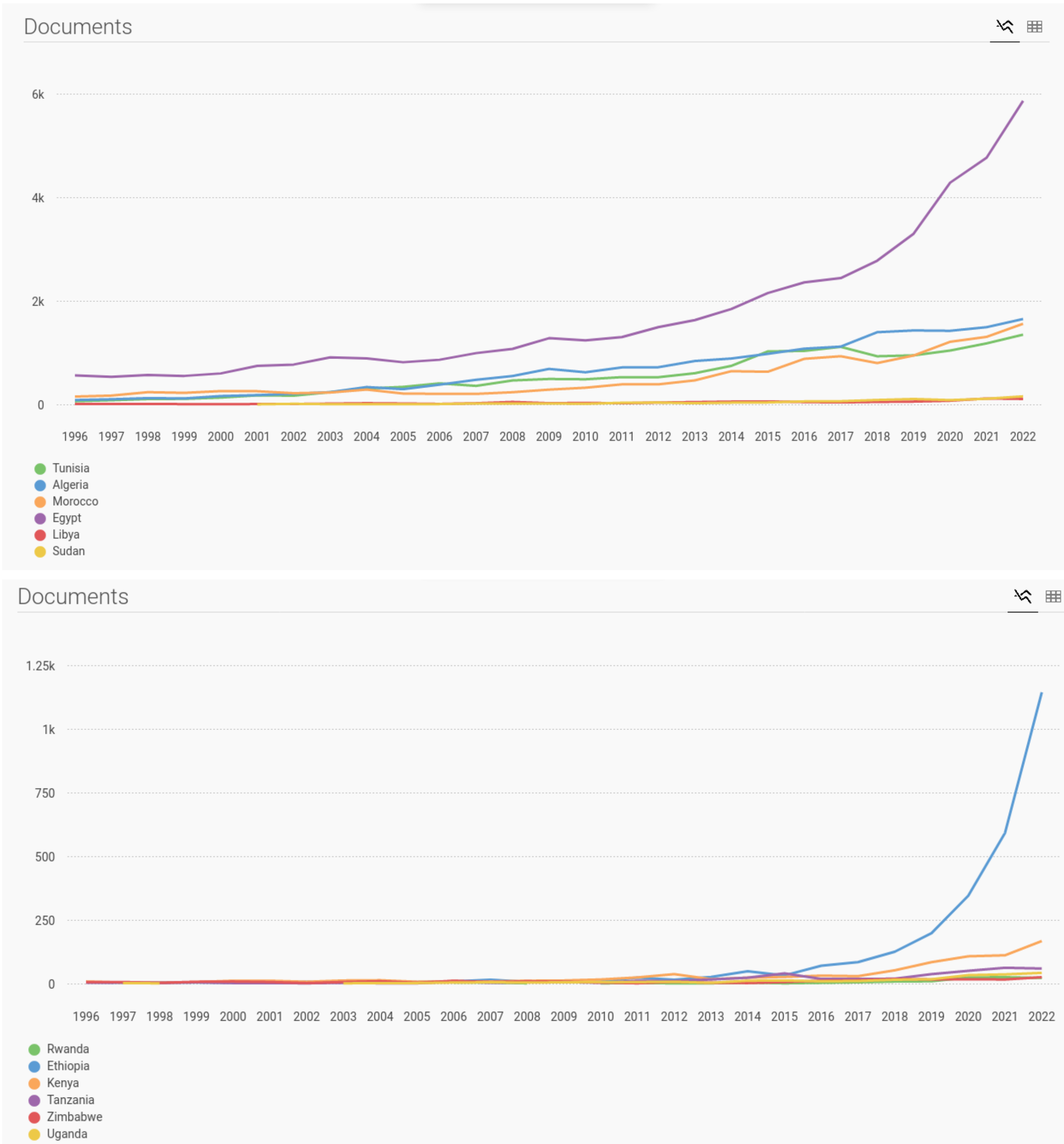

Figure 16-5. *Number of publications per year in Materials Sciences for North and Eastern African countries, after Scimago Scimago.*

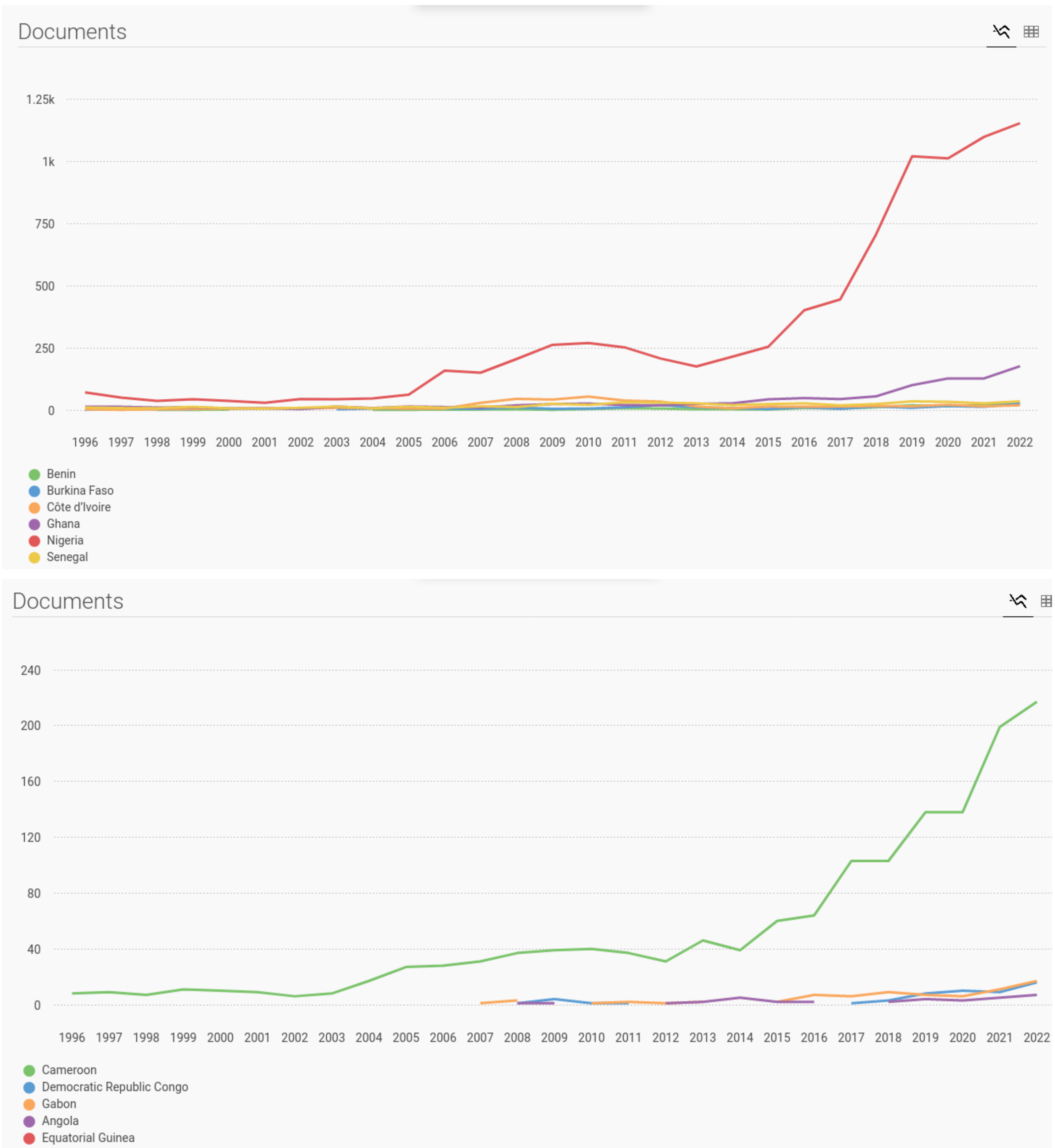

Figure 16-6. *Number of publications per year in Materials Sciences for Western and Central African countries, after Scimago [23].*

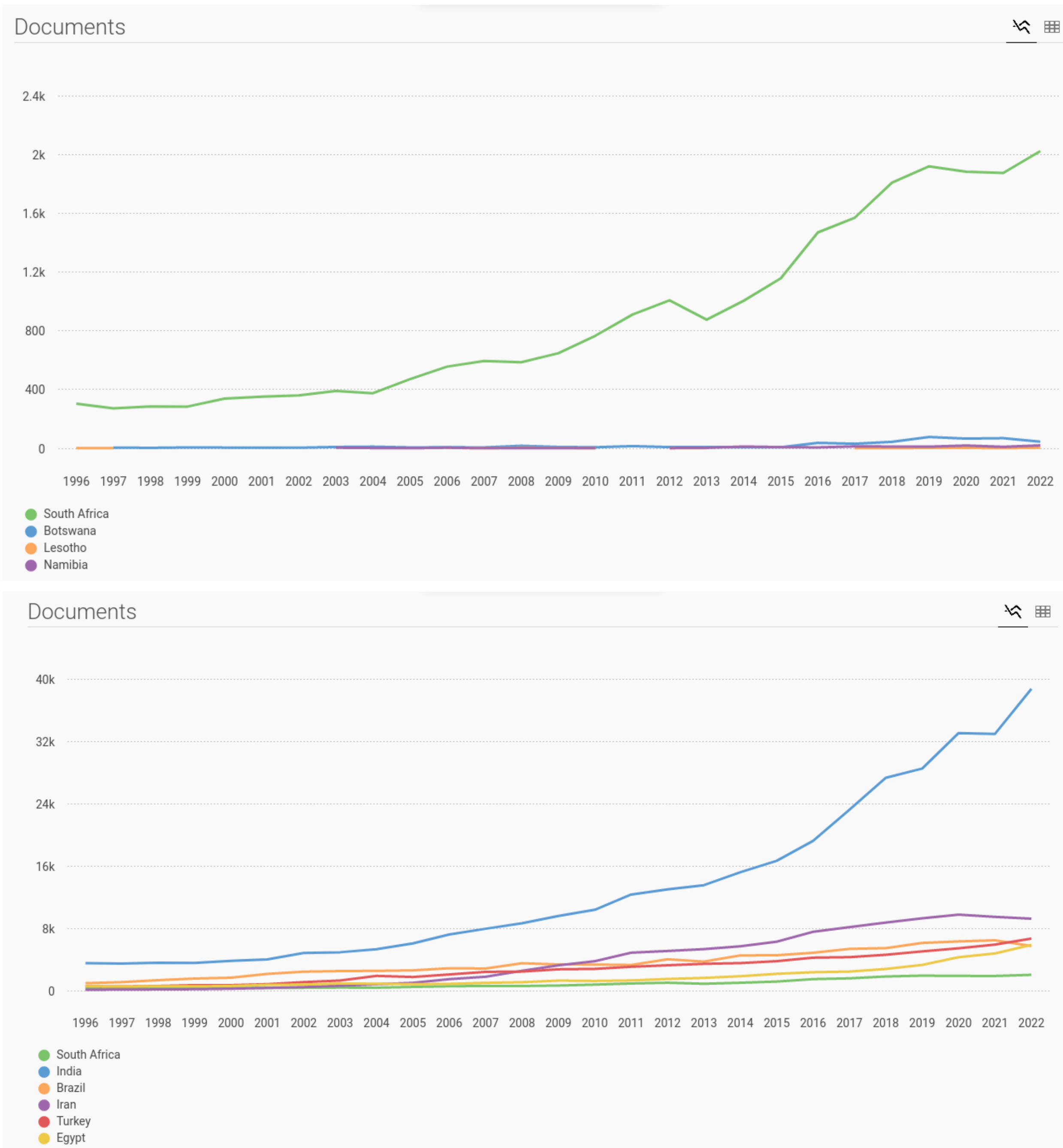

Figure 16-7. *Number of publications per year in Materials Sciences for South African countries, Iran, Turkey, India an Brazil and countries in different continents, after Scimago [23].*