FINAL TECHNICAL REPORT ASSOCIATION OF AFRICAN UNIVERSITIES

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IDRC GRANT / SUBVENTION DU CRDI : - MAPPING RESEARCH INFRASTRUCTURE TO ENHANCE THE RESILIENCE OF SCIENCE SYSTEMS IN SUB-SAHARAN AFRICA

Mapping Research Infrastructures to Enhance the Resilience of Science Systems in Sub-Saharan Africa

Final Technical Report

To the International Development Research Centre (IDRC)

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Association of African Universities (AAU)

30 October 2022

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Executive Summary

The overarching lesson from the impacts of COVID-19 pandemic on Higher Education Institutions (HEIs) is that Africa is poorly equipped in Research Infrastructures (RIs), especially in Virtual RI (VRI) such as data and high-speed internet connectivity, reliable mobile networks and cloud computing facilities that allow for real-time collaboration environments in research, teaching and learning. Adequate RIs (physical and virtual), which include human resources, modern and fully equipped classrooms are essential to success in HEIs research, teaching and learning, especially in the current era of COVID-19 and digital transformations across the globe. As COVID-19 has shown, Virtual RIs (VRIs) is vital to ensuring the continuity of high-quality research, effective teaching and learning. This situation is expected to continue, going forward. However, VRIs need to be accompanied by Physical RIs (PRIs). A vital PRI in Africa is electricity, which still poses significant challenge to HEIs in Africa.

Research goal and objectives

On this backdrop, this project on Mapping RIs to Enhance the Resilience of Science Systems in Sub-Saharan Africa (SSA), focuses on one overarching goal: *to investigate the current RIs landscape, both physical and virtual, in Africa and make recommendations to guide the formulation, implementation and governance of new policies and practices, as well as the revision of existing policies and practices on RIs*.

Specific objectives

The following specific objectives guide the areas of investigations proposed and help establish new links to key stakeholders from Africa and beyond with interest in the topic.

1. Identify gaps in RIs that hinder the growth and resilience of robust research systems in SSA, including specific disciplinary fields or communities of practice.
2. Identify the existing and emerging RIs that SSA HEIs can benefit from and opportunities for access to emerging research technologies on a global scale.
3. Establish new links to key stakeholders from SSA and beyond (including public and private sector actors) with an interest and an ability to mobilise knowledge or resources to improve access to and use of RIs.

Methodology

To achieve the goal of this research, in line with the specific objectives outlined above, which encapsulate the research questions; the methodology deployed in mapping of RIs to enhance the resilience of science systems in SSA project involved: a) extensive desk research of relevant literature [Work Package (WP1)]; b) survey via online questionnaire [WP2]; c) expert interviews with selected actors [WP3]; d) focus group discussions with experts on RIs in SSA [WP4]; e) case studies on RIs in selected HEIs [WP5]; and, f) dissemination and stakeholder engagement [WP6]. The steps involved this methodology helped capture robust data essential to realising the objectives of the research.

Key findings and recommendations

RIs in African HEIs must be conceptualised, designed, operated and managed as a strategic capability, with a long-term view and in a co-creation manner – involving HEIs, industry, government (Triple Helix) and other actors of the ecosystem. Taking this approach can help improve governance, enable collaboration, foster innovation, improve operation, reduce duplication and enhance regulatory compliance and policymaking. Collaborative governance and joint management of RIs will help ensure equity in access, reduce marginalisation and achieve the goal of leaving no one behind.

Governments across Africa need to develop long-term strategic roadmaps for RIs development, alongside R&D and STI ecosystems strengthening. Currently, the majority of international donor funds for research do not include provisions for RIs development as they focus, predominantly, on the implementation of research projects. This dependence on development partners must change as it has implications for the development, sustainability, resilienc,e and science systems strengthening in Africa. Addressing the many gaps identified in our findings require interventions on many fronts and active collaborations.

Collaboration in this sense must go beyond HEIs but also involve an invitation to the private sector to share experiences and expectations with HEIs and R&D. In addition, there a is need to develop and promote virtual infrastructure (e.g., virtual libraries and digital technologies) as this can help enhance access to resources for STEM research. And encourage collaboration among universities and research centres.

Rather than rely on Europe and other continents, the promotion of intra-Africa collaboration is vital. Aside from the advantage of joint fiscal strength to develop RIs, it will encourage sharing, promoting unity, research, and development in SSA. Intra-Africa collaborations can help address current gaps and provide relevant solutions for the region. In addition, intra-Africa collaboration can help promote capacity building to attain a critical mass. The gap between Anglophone and Francophone Africa would also reduce, if this was promoted against the colonial legacy. Collaboration was considered beneficial and a key source for resourcing RIs and promoting research and development. The existing collaborations must be strengthened and enhanced within countries and across countries.

Research and knowledge sharing at institutional, national, and global levels is the bedrock of innovations. This calls for strategies to provide free and better access to knowledge. Open access must be promoted in respect of published literature and bibliographic databases for the benefit of African scientific institutions where funding for accessing these knowledge resources is limited or even lacking.

As captured in the Continental Education Strategy for Africa 2016-2025 (CESA 16-25), there is now increased recognition, at high policy levels, of the importance of RIs in achieving

Africa's socioeconomic development objectives. This improved awareness and recognition is essential to strengthening and prioritising the development of RIs across the continent. Nevertheless, it is far from clear how best to formulate, implement, evaluate and govern policies, strategies and frameworks on RIs at regional and continental levels to ensure mutually reinforcing and complementary benefits for countries in Africa.

Adequate RIs are vital for Africa's excellence in research that contributes to addressing Agenda 2063 and global challenges encapsulated in the United Nation's global Sustainable Development Goals (SDGs). Therefore, the development, management and governance of RIs in Africa must be at the core of the national, regional and continental efforts to advance Africa on the economic, social and environmental fronts.

High-quality research is not only essential to generate innovation and contribute to achieving national development and economic priorities; it is also fundamental to realising the SDGs. In Africa, universities have emerged as the leading RIs amenities. The disruptions in research, teaching, and learning in HEIs brought about by the COVID-19 pandemic have brought to fore the importance of quality RI in Higher Education. The disruption also exposed the gaps that need to be addressed swiftly to position Africa at a place where it will fully take advantage of technological revolutions for its prosperity. Our findings bring us to several recommendations that can enhance the resilience of science systems in Sub-Saharan Africa.

Recommendations

I—Recommendations to HEIs in Africa

The AAU, with support from relevant partners, such as the IDRC, should engage with HEIs within the AAU's network[1] to:

i. Conduct a comprehensive mapping of RIs in HEIs and declare/publish the available equipment and other resources for research on the relevant locations, such as, websites.
ii. Formulate, develop, implement, and maintain RI roadmaps and plans to support regular mapping[i].
iii. Establish adequate institutional arrangements to ensure effective governance, implementation, and M&E of RI roadmaps and plans in HEIs.
iv. Create internal funding sources and mechanisms for RIs development and maintenance within individual HEIs but also across HEIs at regional and national levels.
v. Develop a long-term strategy for enhancing competence and knowledge of academic and other relevant staff in educational technologies and virtual applications.

[1] Currently, this is about 450 HEIs and a high number of African Centres of Excellence (ACEs) across Africa. See: https://www.aau.org/subs/membership/?_ga=2.82186645.2030130918.1666181114-1862018326.1657031599 for HEIs and https://ace.aau.org/ for ACEs

vi. Address the “ivory tower” mentality in academia that often hinders effective collaboration with industry and other actors and stakeholders of RI and innovation ecosystems.
vii. Seek out and exploit avenues for co-development, co-funding, co-sharing, co-management and joint governance of RIs with industry (private sector).
viii. Develop strategies for active engagements and collaborations with industry in R&D that results in mutual benefits including joint patents, innovations (in terms of commercialisable products).
ix. Initiate, under the auspices of relevant university governing bodies[ii], inter-institutional RIs that are shared and jointly utilised among neighbouring HEIs. This is vital in cases of high-end and very expensive RIs.
x. On gender, improve research and data collection on women's progression in science to help deepen our understanding of the factors, including politics and power dynamics, that influence the governance of RIs and the implications on the research and academic careers of female scientists. To achieve this, develop, support and strengthen mechanisms to consider females in the STEM disciplines.
xi. On inclusivity, improve research and data collection on the roles that RIs play in the progression of young and early career researchers in science, in addition to the career of professional and support staff. Programmes should allocate a percentage of funds for persons living with disabilities/ physically challenged. ICT facilities should be inclusive and accommodate all individual users' needs.

II—Recommendations to governments – especially at national levels but could also include governments at the levels of RECs and the AUC

The AAU, using its position as “The Voice of Higher Education in Africa”, should work with relevant partners, such as the IDRC, the World Bank and European Commission, to convene high-level meetings with governments. Such high-level engagements will help to:

i. Develop roadmaps and investment plans to guide progress in RIs development at national, regional and continental levels. This is because inadequate funding remains the main challenge for RIs development in SSA. The heavy reliance on development partners to fill the funding and investments gaps must be urgently addressed.
ii. Formulate a set of criteria to guide the mapping (identification and classification) of RIs in Africa.
iii. Increase education, research, and R&D funding, starting with the agreed 1% GERD and 4% investment in education.
iv. Foster networking and collaboration among a) faculty and students in HEIs in Africa, b) among HEIs and c) between HEIs and private sector; thereby promoting innovation.
v. Enhance capacity strengthening to support RIs development and management.
vi. Work with HEI and innovation ecosystems actors and stakeholders to close the gap in virtual infrastructure – starting with data, broadband and internet connectivity costs, reliability and access.

vii. Improve stakeholders' knowledge of the political and economic factors that influence the sharing of RI funding, human resources development, policies and regulations, and related factors.
viii. Address implementation gaps in current policies that relate to HEIs and innovation; in doing so, emphasise the centrality of RIs. Where applicable, revise / update current policies and deepen understanding of underlying issues that hinder RIs in HEIs across Africa.
ix. Address governance – including coordination, collaboration and accountability - challenges – alongside structural barriers that disincentivise interactions, co-creation and co-learning among HEIs.
x. Explore avenues to improve contributions of the African Diaspora in RIs development, management and governance.
xi. Examine the (dis)incentives for private sector actors to engage in RIs development, management and governance. For example, the use of policy instruments such as R&D tax credits, or avenues to enhance co-purchasing, co-location, co-hosting, and sharing facilities between industry and HEIs.
xii. Improve interactions and cooperation with the private sector, promote technology hubs and venture capitalists. In doing this, strengthen linkages among R&D, NSI/STI ecosystem actors and stakeholders.
xiii. Enhance capacity building among African researchers especially through regional and North-South partnerships and enhance Public-Private Partnerships in more purposeful manner.

III—Recommendations to development partners / external funders

The IDRC, should lead in this area, working with other development partners which are active in the African HE landscape, such as SIDA, the World Bank, the European Commission and Carnegie Corporation of New York, to help ensure that research, funding and project proposals and implementation strategies:

i. Include components for building or improving relevant RIs in research funding calls and innovation programmes and projects. Funding in this regard reflects the priority on RIs in research projects and helps to highlight the importance of RIs to national governments and ecosystem actors.
ii. Increase efforts to address contextual challenges and the roles that RIs can play in this regard to fostering international collaboration in research projects which enhance capacity and competence in African HEIs.
iii. Foster engagements with government, private sector and other key stakeholders as this is crucial to enhancing the building and sustainability of research projects in RIs in Africa.
iv. Encourage joint applications between HEIs and industry actors in funding research projects in Africa,
v. Include RIs, as dedicated thematic areas, in research project calls and funding.
vi. Support HEIs in setting up dedicated state-of-the-art research centres in each African country. This will improve access, mitigate brain drain, and boost skills retention.

IV—Recommendations to private sector at national levels in Africa

Private sector actors are either unaware of the RIs challenges or lack the capacity or interest to contribute to the transformative change that is required in this area. To this end, the AAU, working with key selected development partners and government agencies, should engage with private sector actors in ways that help improve their (private sector actors's) prospects to:

i. Adopt an open-minded approach to collaboration with HEIs in R&D that aligns with national contexts and development goals.
ii. Invest in RIs that contribute to innovation in individual industry's and organisation's lines of business. For example, the case of Guinness, Ghana, which uses local sorghum in the development of drinks and beverages.
iii. Volunteer to open up research and innovation facilities for capacity building to HEIs in areas such as training and internships while at the same time benefiting from the knowledge transfer that emanates from HEIs to industry.
iv. Establish strategies for active engagements and collabotations in research with HEIs.
v. Foster greater appreciation of the role of HEIs in research and innovation that underpins production and industrial growth; and the importance of RIs in the processes involved. With this in mind, work with HEIs in expediting actions on RI development, co-funding, colocation, co-hosting and sharing of facilities.

Acknowledgements

The project team would like to acknowledge and thank the International Development Research Centre (IDRC), Canada, for commissioning the project. We are particularly grateful to Mr. Matthew Wallace, IDRC staff, for his support, inputs and advice throughout the project.

We would also like to thank the many individuals who co-operated with the fieldwork for this project, giving up their valuable time to provide survey responses, offer interviews or participate in the focused group discussions. Thank you all!

Our final gratitude goes to the Secretay General, staff and management of the AAU.

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Acronyms and Abbreviations

4G	Fourth generation of broadband cellular network technology
5G	Fifth generation of broadband cellular network technology
AAS	African Academy of Sciences
AAU	Association of African Universities
ACE	Africa Higher Education Centres of Excellence
ACE I	Africa Higher Education Centres of Excellence first phase
ACE II	Africa Higher Education Centres of Excellence second phase
AEA	Atomic Energy Authority
AESA	Alliance for Accelerating Excellence in Science in Africa
AFD	Agence Française de Développement (French Development Agency)
AI	Artificial Intelligence
AOSTI	African Observatory for Science, Technology and Innovation
ARC	Agricultural Research Center
ASTI	Agricultural Science and Technology Indicators
ASTII	African Science, Technology and Innovations Indicators
AU	African Union
AUC	American University in Cairo
AWARD	African Women in Agricultural Research and Development
CAPREx	Cambridge Africa Partnership for Research Excellence
CAS	Chinese Academy of Sciences
CDT-Africa	Centre for Innovative Drug Development and Therapeutic Trials for Africa
CGIAR	Africa Consultative Group on International Agricultural Research
CHPC	Centre for High Performance Computing
CND	Center of Nanoelectronics and Devices
CO2	Carbon (IV) oxide
COVID-19	Coronavirus Disease of 2019
CSIR	Council for Scientific and Industrial Research
DAAD	German Academic and Exchange Services
DIRISA	Data Intensive Research Initiative of South Africa
DSI	Department of Science and Innovation
ECOPOST	ECOWAS Policy on Science, Technology and Innovation
ECOWAS	Economic Community of West African States
ESFRI	European Strategy Forum on Research Infrastructures
ESRC	Economic and Social Research Council
EU	European Union
FTE	Full time equivalent
GDP	Gross Domestic Product
GERD	Gross Expenditure on Research and Development
HEIs	Higher Education Institutions
HIV/AIDS	Human Immunodeficiency Virus/Acquired Immunodeficiency Syndrome
HR	Human Resource
ICT	Information and Communication Technology
IDRC	International Development Research Centre

IEA	International Renewable Energy Agency
IFPRI	International Food Policy Research Institute
IFS	International Foundation for Science
IITA	International Institute of Tropical Agriculture
IoT	Internet of things
IRD	Institut de Recherche pour le Dévelopement (French National Research Institute for Sustainable Development)
JAES	Joint Africa-EU Strategy
LHC	Large Hadron Collider
LIFE	Liberia Innovation Fund for Entrepreneurship
NACI	National Advisory Council on Innovation
NDP	National Development Plan
NEPAD	New Partnership for Africa's Development
NMIMR	Noguchi Memorial Institute for Medical Research
NMR	Nuclear Magnetic Resonance
NRENs	National Research and Education Networks
NRIC	National Research and Innovation Council
NRIF	National Research and Innovation Fund
NSI	National Systems of Innovation
NTI	Nuclear Threat Initiative
PAERIP	Promoting African–European Research Infrastructure Partnerships
PASET	Partnership for Applied Science, Engineering, and Technology
PC	Personal Computer
PCR	Polymerase Chain Reaction
PE	Political Economy
PhD	Doctor of Philosophy
PPP	Purchasing Power Parity
PRI	Physical Research Infrastructure
R&D	Research and Development
R&I	Research and Innovation
RI	Research Infrastructure
SADC	Southern African Development Community
SALT	Southern African Large Telescope
SANReN	South African National Research Network
SARIR	South African Research Infrastructure Roadmap
SDGs	Sustainable Development Goals
SKA	Square Kilometre Array
SSA	Sub-Saharan Africa
ST&I	Science, Technology and Innovation
STEM	Science, Technology, Engineering and Mathematics
STI	Science, Technology and Innovation
STISA	African Union Science, Technology and Innovation Strategy for Africa
TH	Triple Helix
TIBA	Tackling Infections to Benefit Africa

TIP	Transformative Innovation Policy
TWAS	The World Academy of Sciences
UCL	University College London
U-I-G	University (or Academia), Industry and Government
UK	United Kingdom
UKDS	UK Data Service
UKRI	United Kingdom's Research and Innovation
UNESCO	United Nations Educational, Scientific and Cultural Organization
US	United States (of America)
UVCI	Virtual University of Côte d'Ivoire
UVS	Virtual University of Senegal
VRI	Virtual Research Infrastructure
VUT	Virtual University of Tunis
WACCBIP	West African Centre for Cell Biology of Infectious Pathogens
WANIDA	West African Network of Infectious Diseases ACEs
WHO	World Health Organisation
WoS	Web of Science

1. Introduction

1.1 Research Infrastructure: definitions, scope, understanding and interpretations

There is currently no commonly accepted definition for the term "research infrastructure" (RI)[2]. Scholarly evidence and reports show that there are many definitions, interpretations and conceptualisations of RIs, making it difficult to operationalise the term (Brown et al, 2017). The United Kingdom's Research and Innovation (UKRI) adopts the definition of RI as

> Facilities, resources and services used by the research and innovation communities to conduct research and foster innovation in their fields. They include major scientific equipment (or sets of instruments), knowledge-based resources such as collections, archives and scientific data, e-infrastructures, such as data and computing systems and communication networks and any other tools that are essential to achieve excellence in research and innovation (UKRI, nd, p.9).

The term "research infrastructure" has also been used in reference to advanced research tools such as facilities (laboratories), resources, services (libraries, computing services, grant management systems, research safety and subject protection organisations, secretariat services), platforms, used by the scientific community for conducting top-quality research and for producing novel and influential scholarly output (publications, exhibits, performances (Campbell and Jenkins, 2006)). Broadly speaking, RI includes research funding, the tools, facilities and physical space where the research is conducted as well as the human resources required to carry out research (Toom and Miller, 2018).

Adequate RI is crucial for the production, dissemination and application of knowledge to bring about much-needed innovation and scientific advancement; it is a prerequisite for building capacity in research. Ramoutar-Prieschl and Hachigonta (2020) adopts ESFRI (2018) definition, which refers to RI as **facilities**, **resources** and related **services**, needed by the scientific community to conduct research, transmit, exchange and preserve knowledge. This broad understanding of RI is in line with the interpretations of RI in the global context, as outlined for example in UKRI (nd) and ESFRI (2018).

1.2 Research Infrastructure, Higher Education Institutions in Africa and COVID-19

The disruptions in research, teaching and learning in Higher Education Institutions (HEIs) across the globe as a result of the COVID-19 pandemic has brought to fore the importance of quality RI in Higher Education (HE). The interruptions in research, teaching and learning in HEIs, Universities in particular, in Africa has led to greater emphasis on RI in general but more importantly, virtual RI (discussed further in Section 3.2). Universities in Africa with adequate virtual RI were better placed to continue with activities in their respective

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[2] RI is sometimes used in conjunction with innovation in the form of "research and innovation infrastructure, science infrastructure, or knowledge infrastructure. In this project we use the term "Research Infrastructure"

universities. Examples in this group include the Virtual University of Tunis (VUT), Virtual University of Senegal (UVS), and Virtual University of Côte d'Ivoire (UVCI)[iii]. More importantly, the interferences in HEIs and their (in)ability to continue normal business operations – as a result of COVID-19 pandemic and gaps in virtual RI needed – has exposed deep inequalities in education, digital divides and social structures in Africa.

The overarching lesson from the impacts of COVID-19 pandemic on HEIs is that Africa is poorly equipped in RIs, especially in virtual RIs such as broadband data, high-speed internet connectivity, reliable mobile networks and cloud computing facilities, that allow for real-time collaboration environments. One reason for the gap in this area relates to costs. For example, the cost of mobile data in Africa is reported to be one of the highest, globally (A4AI, 2020). Adequate RIs (physical and virtual), which includes human resources, modern and fully equipped classrooms in HEIs, particularly in the current era of digital transformation. Relatedly, RIs are vital to ensure high quality research, effective teaching and learning, especially in the current COVID-19 pandemic global climate and going forward.

1.3 Research Goal and Objectives

On the backdrop of the preceding discussions, this project on **Mapping RIs to Enhance the Resilience of Science Systems in Sub-Saharan Africa (SSA)**, focuses on one overarching goal: *to investigate the current RIs landscape, both physical and virtual, in Africa and make recommendations to guide the formulation, implementation and governance of new policies and practices, as well as the revision of existing policies and practices on RIs*.

Specific objectives

The following specific objectives guided the areas of investigations proposed and makes new links to key stakeholders from the continent and beyond with an interest in the topic.

1. Identify gaps in RI that hinder the growth and resilience of robust research systems in SSA, including specific disciplinary fields or communities of practice therein.
2. Identify the existing and emerging RIs that SSA HEIs can benefit from, and opportunities for access to emerging research technologies on a global scale.
3. Establish new links to key stakeholders from SSA and beyond (including public and private sector actors) with an interest in and an ability to mobilize knowledge or resources to improve access to and use of RIs.

Based upon the foregoing objectives, which inform the research questions that project seeks to address, we hypothesized that gaps in the current RIs landscape in SSA exist. This project seeks to provide insights into these gaps to help inform possible policy and programmatic interventions in RI in HEIs. The three specific objectives outlined above are used to organise and structure the empirical sections (Sections 3, 4 and 5) of this report.

2. Methodology and underpinning theoretical frameworks

2.1 Summary of Methodology

To achieve the goal of this research, in line with the specific objectives above, which encapsulate the research questions, the methodology deployed in mapping of RIs to enhance the resilience of science systems in SSA project involved: a) extensive desk research of relevant literature [Work Package (WP1)]; b) survey via online questionnaire [WP2]; c) expert interviews with selected actors [WP3]; d) focus group discussions with experts on RIs from SSA [WP4]; e) case studies on RIs in selected HEIs [WP5]; and, f) dissemination and stakeholder engagement [WP6]. The steps involved in this methodology helped capture robust data essential to realising the objectives of the research. The detailed methodology is presented in Annex 1.

2.2 Theoretical and Analytical framework

High-quality research, enabled by adequate infrastructure, is essential to realising Africa's long-term development aspiration of becoming a knowledge-based economy, as articulated in Agenda 2063 (AUC, 2015a/b). In addition, RI is crucial to ensuring that innovation contributes to achieving national development objectives in Africa and economic priorities, while addressing the sustainable development goals (SDGs) (AUC, 2014; Daniels et al, 2021). As the focus of this project is on strengthening Africa's science and research systems in HEIs, alongside innovation systems in the broader societal contexts, the theoretical framework draws from the i) National Systems of Innovation (NSI) (Freeman, 1987; Lundvall, 1992, 2010; Nelson, 1993), ii) Triple Helix (TH) (Etzkowitz, 1996; Ranga and Etzkowitz, 2013; Daniels et al, 2017) of University, Industry and Government (U-I-G) and iii) the Transformative Innovation Policy (TIP) approach (Schot and Steinmueller, 2018; Daniels et al, 2020a). These theoretical frameworks guide the data collection and analyses, as we discuss further in sections that follow.

The NSI and TH frameworks help to explain the interactions among science and research ecosystem actors. Hence, they are adequate for informing the selection of science and research systems data collection. And the analysis of data from multiple actors and stakeholders in the research, science, technology and innovation (STI) systems, and STEM fields.

The NSI and TH frameworks are widely utilised in STI policy processes and policymaking in African countries. For example, the South African National Development Plan (NDP) "embraces the concept of the triple helix whereby government, universities and the private sector aid in the translation of basic research into commercially viable products, processes and services" (Ramoutar-Prieschl and Hachigonta, 2020, p.7). Likewise, many of the current STI policies across Africa make reference to the use of the NSI as the guiding framework.

However, the NSI and TH frameworks are less adequate for providing deep insights on the relationships between research and STI on the one hand, and sustainability and transformation on the other hand. The interventions designed to respond to the impacts from COVID-19 pandemic, has necessitated a renewed focus on the SDGs, reconceptualisation of research and innovation, and greater emphasis on inclusive innovation (Chataway et al, 2014; Cozzens and Sutz, 2014; Foster and Heeks, 2014; Daniels, 2017). The Transformative Change (or TIP framework) provides a deeper connection between innovation, transformation, the SDGs and issues of resilience and long-term transformative change (Schot and Steinmueller, 2018; Daniels et al, 2020a). Therefore, TIP complements TH and the NSI in this regard.

Lastly, Political Economy (PE) ideas are needed in that they help explain how politics and economic factors shape and influence, for example, research or research and development (R&D) funding, thereby to what extent science systems strengthened or not (Chataway et al, 2019). PE framework deals with factors such as ideas, narratives, institutions and governance [including structure and coordination]) that influence and shape science and innovation systems (Daniels et al, 2020b). Consequently, this research draws from TIP and PE as complementary frameworks to the NSI and TH. These frameworks guided the data collection and analysis that inform the findings, conclusions and recommendations made in this report.

Using Agriculture and Food Systems (see Section 4.2 for detailed discussion) as example, the mobilisation of political support for agricultural research has been challenging mainly due to the longevity of time between investments and results as well as the uncertainty of high returns on research (Lyman et al., 2012). Lyman et al. (2012) stress that the volatile nature of donor funding is compounded with a shift from national to regional initiatives, which leaves smaller countries incapacitated and having to deal with vulnerable research systems. In addition, agricultural research in Africa has been limited with the majority of it occurring in South Africa and focusing primarily on hybrid maize (Lyman et al. 2012[iv]).

Beintema and Stads (2014) observed that bulk of the research fund goes into salaries, leaving comparatively small shares to support the actual day-to-day costs of running research programs. In this example, therefore, we find the role of politics (political cycles) and economic considerations (the need to ensure salary payments and maintain jobs – HR factors) resulting in significant implications on the funding for RI, thereby, potentially weakening the science systems.

The mapping tools deployed helped to identify gaps, document the available and emerging RIs that are capable of strengthening the science system in SSA, as well as review the necessary conditions required for the functioning of an effective and efficient RI. The methodology adopted (see Annex 1) and the underpinning conceptual/analytical frameworks details how data were collected and analysed in response to each specific objective and research question outlined above. The activities outlined in the methodology helped to achieve the objectives of the RIs project.

3. Gaps in Research Infrastructures that Hinder the Growth and Resilience of Science Systems in SSA

The discussions, data and analyses in this section respond to the first objective of this research, which is to: "Identify gaps in RIs that hinder the growth and resilience of robust research systems in SSA, including specific disciplinary fields or communities of practice therein".

3.1 The broad categories and conceptualisations of RIs

In addition to teaching and learning in HEIs, good RIs are essential to excellence in science and research, which are important to economic development, social progress and competitiveness (Chataway and Daniels, 2020; Kraemer-Mbula et al, 2020). Infrastructures for research come in various forms, shapes and sizes and perform varied functions. RIs can be physical, single-sited, that is, a single facility; or a resource or service, based at a single location – such as the laboratories of science departments of universities and other educational institutions. RIs can be also dispersed, in this case it could be a network of distributed research equipment, facilities, resources or services such as the Square Kilometre Array (SKA) in South Africa (see Box 1 below).

There are also cases where RIs are virtual – in this case the facility can be hardware, software or service that is provided electronically, for example in the cloud, such as cloud services and cloud computing. Although cloud-based, virtual facilities may be accessed through single or multiple entry points (ESFRI, 2011). These broad categorisations of RIs into physical or virtual are not evident in the SSA research and innovation (R&I) ecosystems, although physical or virtual RIs exist in SSA, based on the data gathered in this research. This is an important gap, which we revisit in the later sections of this report. We unpack these broad conceptualisations and categorisations – Physical RIs, Virtual RIs and RIs by functionalities - further in the sections that follow and discuss the conceptualisations of RIs in the global scene (Section 3.2), RIs in Africa (Section 3.3) and RIs based on functionality and complexity (Section 3.4). Thereafter, we present the empirical evidence from this research.

3.2 Global conceptualisation of RIs

The concept of RI and their role in scientific and technological advancement are well understood by the key actors in STI. RIs comprise facilities, resources and related systems of services which enable research communities to conduct their unique and top-level activities (ESFRI, 2011). Globally, the concept of RIs cover major scientific equipment or sets of instruments, including telescopes or accelerators; knowledge-based resources such as collections, archives or structures for scientific information; enabling ICT-based infrastructures such as grid and high-performance computing, software and high-speed communication networks (also referred to as e-Infrastructures) among others (PAERIP, 2019).

In the Second Action Plan of the Joint Africa-EU Strategy (JAES) (2011-2013), RIs were recognized as a priority focus for Africa-EU science and technology cooperation. In this regard, PAERIP was initiated from 2011 to 2013 to examine how Africa-EU RI partnerships could be enhanced as part of the overall Africa-EU S&T partnership to advance sustainable development. PAERIP was coordinated by South Africa's Department of Science and Innovation (DSI) with part funding from the European Commission. They identified and assessed RIs available on the two continents, existing and potential collaboration and the related issues for research and partnerships (PAERIP, 2019). Although there were no scientific and technological outputs from the implementation of PAERIP, the project produced significant outcomes and with important policy recommendations. These include:

i. RIs should be a priority focus of bi-regional Africa-EU cooperation in STI.
ii. The emphasis on global partnerships as essential component for the development of RIs; individual countries or regions cannot do it alone.
iii. RIs should be harnessed for scientific advancement and innovation on both continents (PAERIP, 2019).

Besides the European Commission as discussed above in the Africa-EU partnership (PAERIP, 2019), the United Kingdom (UK) and other global actors are actively involved in prioritising RI as a way of promoting innovation, enhancing economic growth and addressing the SDGs (UKRI, n.d.). In addition, a growing number of countries have established national frameworks for the prioritisation of RIs. Such prioritisation has helped in budget allocation, allows for long-term financial commitment and improves political support for RIs (Toom and Miller, 2018).

3.3 The concept of RIs in Africa

RIs provide immense opportunities to train scientists and engineers while facilitating knowledge, technology transfer and innovation especially in HEIs. The efforts to advance STI to drive socio-economic development must begin with the establishment and redeployment of robust RI in universities and other HEIs. The current definitions and framing of RIs in Africa have largely followed the ideas and conceptualisations by global actors, which considers RI as facilities, resources and related services. There is need to contextualise these ideas, definitions and framings and ensure that they are meaningful and relevant to African HEI ecosystems.

Any initiative to map RI in Africa needs careful conceptualisation, planning and execution to effectively address the key challenges and ensure a useful exercise for the purposes intended. Such mapping can be informed by some of the works already done. For example, Brown et al (2017) undertook the mapping of food and health RIs in Europe. This study highlighted the challenging nature of identifying and classifying RIs as there appears to be no objective measure. With the increasing pace of technological advancement, RIs are dynamic and constantly developing (Brown et al, 2017). For the particular domain of the study, that is, food and health research, the highly multi-disciplinary scientific nature brings additional complexities. Yet, there are opportunities for adaptability, flexibility and innovation especially as new demands for research emerge in various directions including processes and products to address the global food and health challenges.

To address the challenges in the identification and classification of RIs, a study of RIs needs a well-formulated set of criteria to guide the process. Such a set of criteria is best determined with a reference to the context of the study. However, the basic constitution of the RI is a fundamental criterion. For example, to qualify as an RI, a facility must be a built laboratory with the full complement of scientific equipment, network facilities and the requisite utilities – water, electricity and internet connection. An adequate team of human resources to ensure functionality is also a necessity. However, a number of questions arise beginning with issues of limitation or scope and extending to standards/quality and scientific thematic focus. How large should the built laboratory be – for it to qualify or be identified as an RI? What are the standards for the equipment in the laboratory – a 1990 electron microscope versus a 2020 electron microscope brings out clearly the contrasts in sophistication and functionality.

Besides the gap in age, other factors such as functionality, precision and sophistication in delivery on the tasks matter. In terms of human resource (HR), what level of staffing of the scientific workforce is acceptable? The total number of scientists and technicians in full employment or with some part-timers and interns? Furthermore, context comes into play when utility supplies are considered – a 4G internet connection or 5G? What range of bibliographic databases should qualify the RI to be identified and classified? Clearly for this study being led by the AAU, an important precursor is the formulation of a set of criteria to guide the identification and classification of the RIs. To help unpack these further, we explore different types of RIs, using the case of South Africa.

3.2.1 Physical RIs in Africa

Physical RIs (PRIs) refer to physical facilities, whether single-sited RIs (found at a single location) or distributed (part of a network of distributed resources across regions and/or countries), required to develop new knowledge and/or technology. They include research universities, scientific equipment (basic and advanced), science and technology parks, incubators, technology parks, technology transfer offices, laboratories, observatories, specialised facilities, and consumables. Of these, research universities are at the centre of the global knowledge economy and are the most visible academic institutions (Altbach, 2013). There are also research institutions with specific mandates in particular sectors of the economy such as agricultural research institutions (such as the International Institute for Tropical Agriculture (IITA) in Ibadan, Nigeria) and industrial research institutions (such as Council for Scientific and Industrial Research (CSIR) in South Africa).

The IITA with headquarters in Ibadan, Nigeria, typifies a research institute, which is well-endowed with physical infrastructure to address its mandate. It has modern and state-of-the-art laboratories to provide analytical services for a wide range of testsIITA's biotechnology and molecular biology laboratory includes the Molecular Genetics Lab based in Yaoundé, Cameroon and the Biosciences Centre based in Ibadan, Nigeria. There are also the Food Utilisation and Nutritional Lab and the Pathology Laboratories. These RIs add up to create an assemblage of facilities at the headquarters and the other stations in Central, West, East and Southern regions of Africa. Altogether, there are hubs and stations in 11 countries in sub-Saharan Africa.[v] The CSIR of South Africa is similarly endowed with the needed physical facilities to enable the conduct of cutting-edge research.

Electricity is a vital component of PRIs. However, many countries in Africa have continued to struggle with access to reliable supply of this critical resource generally. Electricity access rate in Africa is only 40 per cent. The per capita electricity consumption is 180kWh in Africa whereas it is 6,500kWh in Europe[vi]. Unreliable electricity supply affects RI operations and adds to the operational costs where supply has to be stabilised. In order to address issues arising from poor access to electricity, there is a need for long-term energy planning, evidence-based decision making, exploitation of versatile solutions and political commitment to achieve this feat (IEA et al., 2019).

There are various reasons why modern PRIs are important. First, researchers are able to conduct fairly independent and high-quality research, which could address pressing development challenges in sectors such as agriculture, health, industry and the environment. Secondly, modern physical facilities enable international collaboration to address the global challenges, such as the SDGs and climate change. Without modern physical facilities scientists are unlikely to come up with discoveries, inventions that can be patented for industrial applications, and innovations. Assessing Africa's physical research facilities suggest that gaps exist which need bridging to ensure keeping pace with global research. It is in this regard, that programmes such as the African Centres of Excellence (ACE) funded by the World Bank and coordinated by the Association of African Universities (AAU) have been initiated. As noted above, RIs range from the relatively simple to the very complex, which may be located in a single space or scientific facilities distributed across multiple locations, for instance, the Square Kilometre Array (SKA) project, as summarised in Box 1 below.

Box 1: The Square Kilometre Array (SKA) Project

This is an international effort to build the world's largest radio telescope, with eventually over a square kilometre (one million square metres) of high-end data collection area. As one of the largest scientific endeavours in history, the SKA brings together a wealth of the world's finest scientists, engineers and policymakers to actualise the project. The SKA project will eventually use thousands of dishes and up to a million low-frequency antennas that will enable astronomers to monitor the sky in unprecedented detail. This RI will allow scientists to survey the entire sky much faster than any system currently in existence. Its unique configuration will give the SKA unrivalled scope in observations, largely exceeding the image resolution quality of the Hubble Space Telescope of the US

space agency, NASA. Both South Africa's Karoo region and Western Australia's Murchison Shire were chosen as co-hosting locations for many scientific and technical reasons, from the atmospherics above the sites, through to the radio quietness, which comes from being some of the most remote locations on Earth. Whilst 14 member countries are the cornerstone of the SKA, around 100 organisations across about 20 countries are involved in the design and development of the SKA. In 2020, The cost of the SKA including construction and the first 10 years of operations (2021-2030) is estimated to be around 1.9 billion euros in 2020 euros.
Source: Adapted from https://www.skatelescope.org/the-ska-project/ accessed 10th February 2021.

3.2.2 Virtual RIs in Africa

Virtual RIs (VRIs) is sometimes referred to as e-infrastructure, virtual research environments, digital, or cyber RI. VRI, refers to information and communication technology (ICT)-based infrastructures such as data storage and management systems, grid and cloud computing infrastructures, high performance computing systems, and broadband research networks (BCSD, 2019). Other examples in this category include advanced instrument and data repositories, visualisation environments, archives, databases and data banks such as biobanks, research analysis software platforms for processing and analysing data, digital libraries, computational tools, and people trained to effectively manage these infrastructures with the aim of boosting research productivity. VRI covers all infrastructure that enables digital/computational research. VRIs can be regarded as 'scientific instrumentation'. To help illustrate the point, Figure 1 below presents the building blocks of VRIs, using the UK's current national research and innovation e-infrastructure ecosystem as an example.

Figure 1. The building blocks of e-infrastructure

Networks	International/national (GÉANT and Janet), local
Software	Tools (operating systems, digital and software libraries, access management systems etc.) Application codes (modelling, simulation, data analytics)
Computers	Supercomputers High-throughput computers for data analysis
Data infrastructure	Infrastructure for moving, storing, analysing, visualising and archiving data
Access mechanisms	Cloud technologies Access management and identity management technologies

Source (UKRI, nd, p.99)

As pointed out above, the COVID-19 pandemic has highlighted the gaps, but also, the importance of VRI in Africa's HEIs. The emergence of virtual means of working and interacting has placed premium on internet connections. Participation in virtual meetings, workshops and conferences through the various media platforms, search for information and dissemination of information in cyberspace depends on strong and reliable internet connectivity. Currently, Africa has the lowest internet access in the world at 22 per cent compared to Asia and Pacific of 44 per cent, 66 per cent of the Americas and 80 per cent of Europe. The African Union aims to connect every organisation, business and individual on the continent by 2030 with the assistance of the World Bank[vii]. This is crucial given that the virtual mode of interaction, communication and business engagements, public and private, is likely to increase as virtual work culture becomes the new 'normal'.

A critical foundation for VRIs is access to high-speed, broadband internet connectivity (BCSD, 2019), which is an area of major challenge in Africa. The global COVID-19 pandemic has revolutionised several spheres of life, including research, and buttressed the need for adequate VRIs, as exemplified in the shift to online education – teaching and learning. There have been efforts in recent years to build VRIs in Africa. For example, the European Commission-funded eI4Africa Project, which ended in October 2014 was designed to boost the Research, Technological Development and Innovation (RTDI) potential of African e-Infrastructures within the framework of the Joint Africa-EU Strategic Partnership. The main outcomes include some state-of-the-art e-Infrastructure applications in Africa, a project wall showcasing 34 e-Infrastructure projects in Africa and the Africa Grid Science Gateway, which is a portal for researchers to access e-Infrastructure applications[viii].

A follow-up to the eI4Africa project is the Sci-GaIA Project – **Sci**entific Endeavour through Science **Ga**teways and e-**I**nfrastructures in **A**frica. Sci-GaIA was a 24-month project which ended in 2017, executed with a total European Commission (EC) grant amount of € 1,339,125. The project was aimed at supporting the creation of an African Open (and Linked) Data Infrastructure, interoperable and federated with those existing in the EU and other regions of the world. The main outcome of the project is the creation of the Sci-GaIA Open Access Repository (OAR)[ix]. Noteworthy to mention is the Africa Grid Science Gateway, which was conceived and developed as part of the activities of the eI4Africa project and actively supported by Sci-GaIA. Since 2017, the Africa Grid Science Gateway has been relocated to the Dar es Salaam Institute of Technology (DIT) in Tanzania. It is an important move to develop and deploy e-Infrastructures in Africa.

More efforts continue to be made in developing VRIs in Africa. A notable effort in this regard is the National Research and Education Networks (**NRENs**). NRENs are vital VRIs in that they provide highspeed broadbands internet and networks that enable connections among universities and the research community. Various sub-regional networks have been set up to support NRENs. These include sub-regional networks in the West and Central African Research and Education Network (WACREN), UbuntuNet Alliance for East and Southern Africa, and Arab States Research and Education network (ASREN), which covers North Africa. NRENs have experienced rapid expansion in recent years. However, as Annex 3 shows, the distribution of NRENs in Africa remains uneven, with more presence in the North, East and Southern Africa in comparison to Central and Western Africa (Bashir, 2020). Enhancing NRENs across the continent, as critical VRIs, is vital to fostering research collaborations, which is essential to innovation, improving productivity in HEIs, addressing socioeconomic and development gaols and achieving resilience in post-COVID-19 era in Africa's universities.

Virtual RIs are the present-day reality for advanced research across almost all sectors of the economy. ICT-based infrastructures are at the heart of data collection, storage and analysis. In recent years, the data processing capacity enhanced through supercomputers has been increasing substantially leading to big data science becoming an emerging area of S&T. The application of 4IR suite of technologies – for example, AI and IoT – are underpinned by robust VRIs. Africa is making efforts to keep pace with VRIs within the research systems though gaps appear to be widening for most of SSA, exempting South Africa.

3.4 Research infrastructures based on functionality and complexity

RIs can be classified into six main types based on their functionality and complexity. Table 1 below helps to illustrate the nature and diversity of RIs that are essential in building science systems, thereby provides a basis for classifying RIs.

Table 1: Typology of RIs and Functionality – The Case of South Africa

Type of RI	Description	Examples
1. Research laboratory equipment	This is the minimum level of equipment and facilities that need to be in place as a necessary requirement for conducting basic research and training graduate students.	Analytical NMR spectrometers; equipment for chromatography; and powder X-ray diffractometers.
2. Scientific equipment	Equipment enabling research tools that are fundamental for conducting competitive research and training the next generation of researchers. Scientific equipment refers to dedicated, immovable, free standing, large, networked, multi-user and multi-disciplinary research equipment including all necessary ancillary components such as computers and specialised software, amongst others.	A suite of mass spectrometers based at the Institute of Wine Biotechnology at the University of Stellenbosch in the Western Cape useful in understanding the biology of wine-associated organisms, ecology, physiology, molecular and cellular biology of grapevine, wine yeast/bacteria.
3. Specialised facilities	Dedicated research institutions that house large, unique and highly specialised physical RIs that provides a controlled environment for ensuring the optimal performance of the research equipment as well as conducting highly specialised experiments.	Specialised microscopy facilities, e.g. high-resolution microscopy; bio-repositories; radio-telescopes; research-focused forensic laboratories; biosafety, biohazard, radiation containment facilities.

4. High-end infrastructure	Specialised platforms or laboratories that support a) the transition from R&D to commercialization; b) scalability and reproducibility of products and processes.	Pilot plants, incubators, technology demonstrators and semi-commercial test facilities.
5. Global Research Infrastructures	These are the critical enablers for advancing scientific knowledge, research outputs and innovations, as well as accelerating the training and development of the next generation researchers; may be (i) 'single-sited'[x], (ii) 'distributed'[xi] or (iii) 'virtual'.	The Large Hadron Collider (LHC), the Square Kilometre Array (SKA) project, Southern African Large Telescope (SALT).
6. Cyber-infrastructure	These are ICT-based infrastructures comprising among others (i) high performance computing; (ii) broadband research networks; (iii) data storage and management systems; and (iv) grid and cloud computing infrastructures.	The Centre for High Performance Computing (CHPC), South African National Research Network (SANReN), the Data Intensive Research Initiative of South Africa (DIRISA).

Source: Based on Ramoutar-Prieschl and Hachigonta, 2020

The efforts to promote RIs in Africa and create the enabling environment for their establishment, maintenance and development have been ongoing at national and at sub-regional and international levels for some years. For example, in November 2013, an inception workshop on "Addressing Equipment Challenges in Development-related Scientific Research in Africa" was organized by the International Foundation for Science (IFS) and African Academy of Sciences (AAS). The workshop was a follow up to a conference held in Nairobi in May 2012, titled "Getting and Using Equipment for Scientific Research in Africa". Country studies were conducted in Kenya, Ethiopia and Ghana leading to significant policy recommendations on scientific equipment for the consideration of African governments (IFS, 2012; IFS, 2014; Awuni and Essegbey, 2014).

The country studies highlighted the challenges and gaps in the institutional arrangements and processes for acquisition, operation, maintenance and development of scientific equipment. The findings revealed that the countries studied had built reasonably good S&T systems to facilitate national development. Nigeria, for example, has a science system composed of about 170 universities and research institutions at the Federal and State levels as well as a responsible Ministry for Science, Technology and Innovation. Similar systems exist in the countries that the IFS and AAS partnered in the study of scientific equipment – Nigeria, Madagascar, Kenya, Ethiopia and Ghana. In particular, the institutional frameworks for R&D in these and other African countries have been established with a range of scientific equipment in their laboratories. However, the fundamental challenges such as addressing the SDGs, which the R&D institutions are expected to impact significantly on, are still prevalent.

It is not a lack of formulation of STI policies, but a lack of effective implementation and governance of those policies (Essegbey et al, 2015).

The country case studies on scientific equipment highlighted the fact that not only do African science systems need additional equipment, but also the ecosystem for proper functioning of these scientific equipment requires significant improvements. There were the challenges surrounding the acquisition and use of scientific equipment. Thus, making it difficult for the realization of the dream of facilitating national development through the application of STI.

3.5 Summary of findings based on empirical data

3.5.1 Types of RIs in SSA, gaps, and opportunities for strengthening

Evidence from the study survey established that the most common physical RIs in Africa are the Research Universities, closely followed by Scientific Equipment and then Laboratories. The leading Virtual RIs in SSA is the Internet facility. However, the relatively low broadband research networks and lack of knowledge products in high-performance computing systems imply that African scientific institutions need to urgently upgrade their virtual RIs to be in a position to issue more cutting-edge research. The evidence indicate that availability and usage of Human capacity are very good among the RI in SSA. However, the availability and usage of Fourth Industrial Revolution (4IR) technologies constitute a serious gap in the RIs landscape in Africa.

The three most outstanding sources of funding for RI in Africa are Patent buyouts[xii], Diaspora financing, and Loan Schemes. Inadequate funding is the most serious challenge, limiting access to RIs in Africa. Development Partners have been identified as a major source of funding for RIs in Africa, indicating the need for other sources of funding. Strategies in place for strengthening RIs in Africa, as evidenced by policies, acts, and national strategies are hindered from being efficient because of poor implementation. Allocation of specific budgets for RIs development and maintenance in HEIs and R&D stands out as the most effective strategy for strengthening RIs development in Africa.

3.5.2 Conceptualisation and importance of RIs in SSA

Conceptualisation

The experts interviewed, and the participants in the focused group discussions referred to HEIs as the most common physical RI in SSA. In the SSA context, people are a focal element of RIs – this includes those involved in the planning, conducting, and utilising research results.

Facilities that rely on internet connectivity were cited as the leading virtual RI that SSA countries are familiar with. The human resource component of RIs in SSA was considered satisfactory but scant and threatened by brain drain or skills migration due to the lack of specific RIs or due to poor conditions of service. The experts interviewed and the focused group discussion participants both recommended that an African conceptualisation of RIs foregrounds the importance of virtual resources in the research landscape.

The service aspect of RIs was highlighted as vital for sustainability as the window through which stakeholders access solutions to problems and opportunities for wealth creation. It was noted that services such as quality assurance, monitoring and evaluation, ethics, and policy directions, in general, help to secure and ensure the effectiveness and usefulness of research output while protecting patents and products especially in STEM. Overall, there seemed to be a consensus on the use of a value-chain conception of RIs, as the aggregate effect of all the elements that constitute RIs determines their overall quality and usefulness.

Importance/Role

RIs were acknowledged to support the conduct of scientific research and other knowledge generation ventures by non-academic institutions, teaching and learning in HEIs and R&D. Specific importance of RIs mentioned and discussed by respondents included:

- **Research acceleration**. Robust research systems make research possible, and increase the speed or rate of implementation. RIs catalyse the research processes and ensure effective and prompt delivery and application of research outputs in a market setting.
- **Creating an enabling environment for science and technological development**, leading to innovations and development in our society. Extensive and sustained research helps gather new data and knowledge that enables organisations and nations to invent new technologies and software that further expand and boost the effectiveness of existing RIs. Thus, a robust RI supports the creation of enabling environments for the production and scale up of market-ready solutions.
- **Facilitate economic growth**. Good RI caters for the needs of all sectors of an economy by providing equipment and facilities, resources and services with equal and equitable distribution to undertake research for problem-solving, enhancement and innovation, leading to economic growth.
- **Collaboration**. RI promotes joint-sharing and management, and collaborative work, which are key in promoting access and optimum utilisation of existing RI and increasing research output. Social networking is birthed through international conferences, workshops, and symposia, which promote interaction. Social networking can also help harmonise research practices and standards across nations and continents, promoting exchange and shared development. COVID-19 restrictions have promoted virtual infrastructure use to facilitate collaboration and sustain social networking.
- **ICT RI for knowledge management** facilitates access to information and provides data collection, processing, storage, and retrieval.
- **Competitive advantage**. A country, an organisation, institution or other groups with state-of-the-art RI stand a greater chance of developing better and faster than those with poor RI. This partly accounts for the vast difference between Africa and the West in terms of development.

Feedback from the respondents highlighted the importance of RIs in meeting SDGs and achieving SSA's goal of becoming a knowledge-based economy. It was noted as imperative to accord RIs a crucial place in national development agendas.

4. Existing and Emerging RIs in Higher Education Institutions in SSA

In this section, we identify the existing and emerging RIs that SSA HEIs can benefit from. The discussions also highlight opportunities for access to emerging research technologies on a global scale. In identifying existing and emerging RIs, we examine the state of RIs in Africa (Section 4.1), and explore RIs in Agriculture and Food Systems (Section 4.2), RIs in Health and Medicine (Section 4.3), and RIs in Science, Technology, Engineering and Mathematics (STEM) (Section 4.4). Policies, regulations, standards and frameworks on RIs and HEIs in Africa are examined in (Section 4.5) as these could potentially contribute to the continents ability to exploit opportunities for access to emerging RIs and technologies at regional, continental and global scales – beyond national boundaries. The section ends with discussions on cross-cutting topics – gender and equality, human resources, the role of industries and funding for RIs (Section 4.6).

4.1 State of RIs in Africa

4.1.1 Overview from literature

Although Africa constitute 15% of the world population, it only accounts for 1.1% research and development investment globally and 1.5% contribution to scientific publication (Bashour, 2013). These scholars have identified Africa's inability to provide adequate RI such as laboratories, data processing centres, biobanks and other brick-and-mortar facilities needed for research, especially in universities as well as the failure of international funders to invest in Africa's RI as major reasons for poor research output. In addition, there is fragmentation of current research and academic infrastructure across the region, particularly in STEM. This is a further obstacle to the development of African-led technical solutions.

RI enables scientists to undertake quality and relevant ground-breaking research that helps address societal problems and enhance the quality of life. Through the provision of research tools and equipment, RI forms the foundation for quality research in every discipline, especially in scientific disciplines. Scientists are heavily dependent on RI, making it essentially critical.

Wood et al. (2013) notion of RI is similar to the European Strategy Forum on RI definition of RI as "facilities, resources and related services used by the scientific community for conducting leading-edge research, knowledge transmission, exchange and preservation" (ESFRI, 2018, p.11). Although these framings and understandings of RI are similar and provide a way forward, they do not delineate the boundaries of RIs. Rather they stress the essential equipment, skills and the conducive environment that will aid the researcher to function effectively in the conduct of a research. While the resources or tools are visible, the support services in terms of human resource support, peaceful and conducive research environment are all embedded in the 'related services' which are equally highly essential for a successful research outcome. Therefore, the point needs to be made that delineating the boundaries of RI is difficult given the multi-dimensional nature of RIs.

Furthermore, Wood et al. (2013) opine that RI is an entity of the entire research ecosystem which involves communities with elements such as open services to scientific researchers, national institutions, maintenance and upgrading of strategic plans, training, e-science and access to world-class peer review. Thus technology, human capacity and community support are highly critical to RIs. Other important components of the ecosystem, in line with the NSI framework, are private sector, human resources, funding, policies and regulations (see Section 4.6 for more discussion on these components).

4.1.2 Evidence from empirical data on the state of RIs in Africa

Figures 2 and 3 below present the RIs in Africa, existing and emerging, based on the survey data gathered during this research.

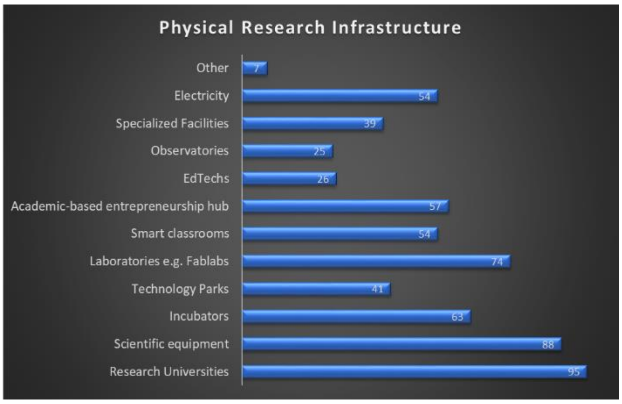


Figure 2: State of physical RI in Africa

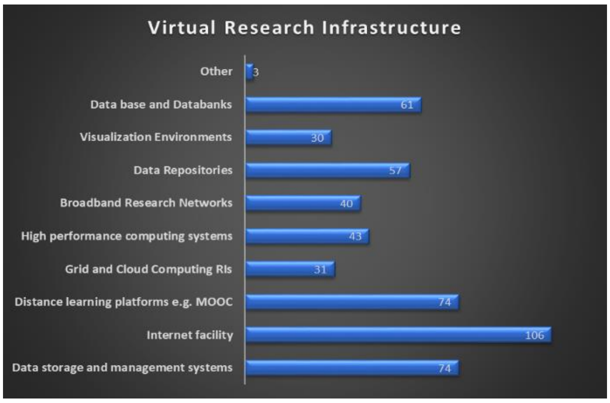


Figure 3: State of virtual RI in Africa

As Figures 2 above shows, the most common Physical RIs in SSA are the Research Universities, closely followed by Scientific Equipment and then Laboratories. Fabrication laboratories (Fab labs) for example, are important for experimenting and designing technologies and products. Fab labs are specialised small-scale workshops equipped with computer-controlled and other digital tools for design and production. In the sample, 74% of the respondents indicated the presence of fab labs in their institutions. This is encouraging. Besides, 63% and 57% indicated as having incubators and academically-based entrepreneurship hubs respectively. These are necessary facilities to promote research outputs from the RIs.

Relatedly, the leading VRI in SSA is the Internet facility (Figure 3). Distance learning platforms and data storage management systems are competitively closing up ranks with the internet facility. Almost 100% of the respondents noted internet facility as part of their virtual RIs and important for communication in research programmes. The relatively low broadband (BCSD, 2019) research networks and high-performance computing systems imply that African scientific institutions need to urgently upgrade their virtual RIs in these areas to get into more cutting-edge research.

In recent years, there has been a global shift from resource-based to knowledge-based economies, with knowledge, as a source of national wealth, viewed as superior to physical capital (Abugre, 2017). As knowledge becomes an increasingly important and necessary player in the present global competition, so have HEIs and R&D departments. The increasing importance of HEIs and R&D have facilitated the surge of enrolment in HEIs in Africa. Our evidence indicates the presence of a good availability and usage of human capacity with respect to RIs in Africa (Figure 4).

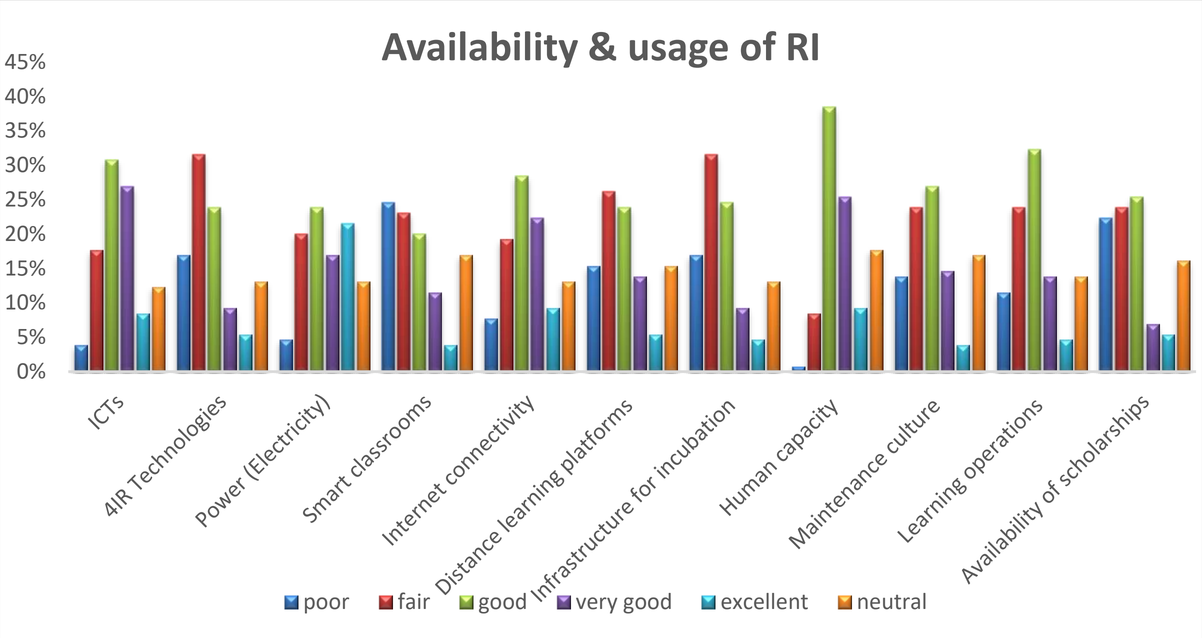


Figure 4: Availability and usage of RIs in Africa

Enabling amenities, such as power supply and internet connection, enabled ICT enhancement in learning-teaching during COVID 19 pandemic. However, the availability and usage of modern amenities, such as smart classrooms, were incredibly low.

Scholarships that can enhance RI and R&D in Africa were reported to be doing extremely poorly, constituting a serious gap in the RIs landscape in Africa. Technologies in 4IR and infrastructure for incubation also leaves much to be desired. 38% of the respondents reported that RIs are largely inadequate in SSA (Figure 5), a finding corroborated by evidence from the expert interviews and case studies on African Centres of Excellence (ACE). This could be largely attributed to inadequate funding (75%) and inadequate RI (67%) as shown in (Figure 6) below.

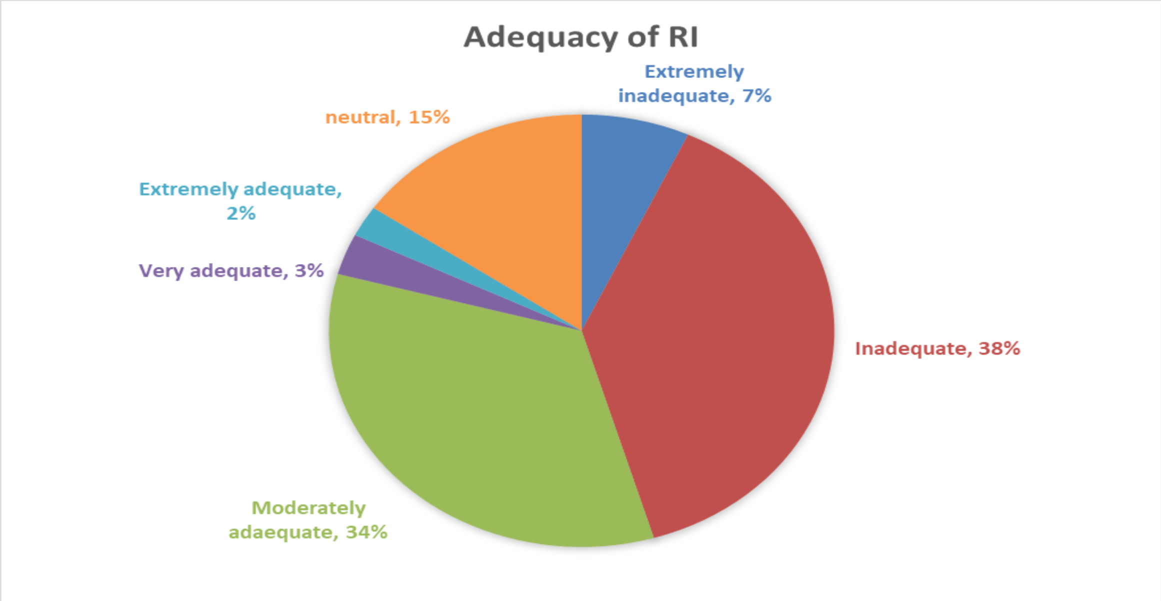


Figure 5: Adequacy of RIs in Africa

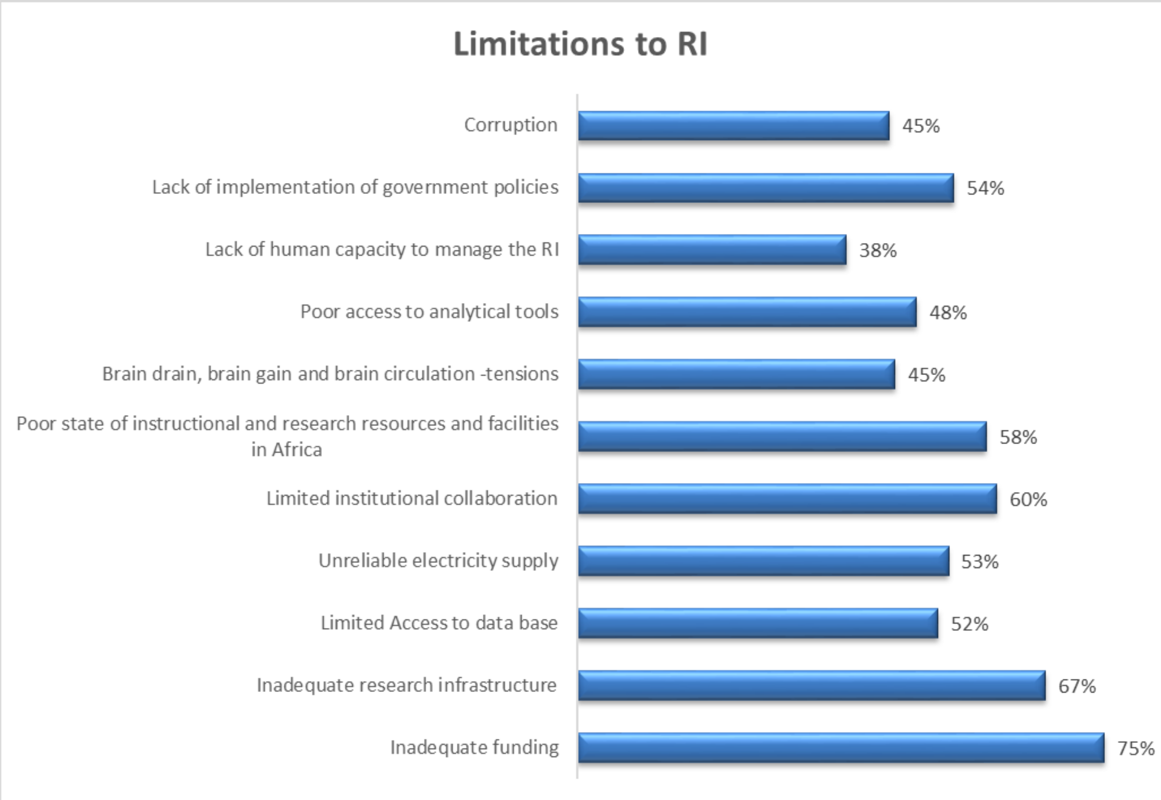


Figure 6: Limitations to RI in Africa

Despite growth in student enrolments in HEIs, the quality of higher education in SSA remains low as compared to developed countries (Ouedraogo, 2017). These findings explain, in part, the absence of African universities in the top 100 in the world or the presence of about 26 universities in the top 1000 universities globally. As a result, significant deterioration of academic infrastructure and research, and subsequent decline in the quality of teaching and research are widely spread across the region (Shende & Reddy, 2020).

In the sections that follow we focus on priority sectors for Africa. In some of the instances, we take a systems of innovation approach and make the relevant connections to the issues at systems level. We start with RIs in Agriculture and Food Systems.

4.2 RIs in Agriculture and Food Systems

RIs provide the essential bedrock for a countries economic development and can be regarded as the primary and required element for the establishment of knowledge economy (Lee et al., 2009). Agricultural R&D is highly critical to increasing productivity and economic growth in Africa, yet African governments consistently underinvest in agricultural research.
Africa currently produces approximately 10% of agricultural output in the world, while occupying 25% of the world's arable land (Delvaux et al., 2020). Agricultural R&D in Africa have experienced similar RI challenges to the wider scientific research systems.

The IFPRI Agricultural Science and Technology Indicators (ASTI) programme provides an illustration of the kinds of issues prevailing in agricultural research in Africa. ASTI offers an open-source data on agricultural research systems across the developing world including some 40 countries in SSA. ASTI works with a large network of national collaborators to collect, compile, and disseminate information on financial, human, and institutional resources at both country and regional levels across government, higher education and other agricultural research agencies[xiii]. The ASTI data and indicators provide some useful insights in agricultural RIs and the related issues.

Table 2: Agricultural S&T Indicators (ASTI) (2016) for Selected Countries in SSA

Country	Research spending in US$ million* (top 6)	Spending as share of agric. GDP %	Researchers FTE	% with PhD	51 years or older	Share of females	% Capital Expenditure
Nigeria	433.5	0.22%	2,975.5	24%	22%	29%	19.9%
South Africa	417.4	2.78%	811.3	-	-	-	
Kenya	222.4	0.48%	1,156.2	40%	46%	30%	6.2%
Ghana	178.6	0.91%	598.9	45%	36%	21%	3.6%
Ethiopia	162.1	0.29%	3,024.6	8%	7%	10%	23.2%
Uganda	99.4	0.62%	558.7	36%	20%	30%	2.3%

*Spending in constant 2011 purchasing power parity (PPP)
Source: Compiled from IFPRI/ ASTI Database https://www.asti.cgiar.org/benchmarking/ssa

As in Table 2 above, total agricultural research spending (excluding the private for-profit sector) in SSA comprising some 40 countries, declined from $2.4 billion in 2014 to $2.3 billion in 2016, measured in constant 2011 purchasing power parity (PPP) dollars. The levels of agricultural spending varied considerably across these countries. Six countries – Ethiopia, Ghana, Kenya, Nigeria, South Africa, and Uganda – spent close to $100 million each or more in 2014/2016. Agricultural research spending for Nigeria and South Africa in 2016 was each in excess of $400 million (ASTI, 2017). This value is reduced if analysed in terms of percentage share of agricultural spending per GDP. Although South Africa's percent share of agricultural GDP is 2.8%, the expenditure is less than one percent for the rest of the countries in Table 2. Nigeria's share is 0.22% while Ethiopia is 0.29% (ASTI, 2017). Such low levels of expenditure have implications for building world class RIs to sustain agricultural R&D in Africa. Agricultural expenditures are classified in three components namely (i) salaries, (ii) operation and programme costs and (iii) capital investment or development. That majority of annual budgets spent on salaries and operations suggest a low priority on building RIs for agricultural research and development (ASTI, 2017).

There are also issues with the numbers of human resources essential to the effective functioning of research institutions in Africa. There is capability to formulate and effectively execute research programmes which address contextual challenges that contribute to addressing food security and nutrition challenges, and foster agribusiness. The countries listed in table 1 illustrate a general trend on the continent in Sub-Saharan Africa. Full time equivalent (FTE) indicators showing the extent to which human resource is committed to R&D, is relatively low in Africa. Nigeria's FTE of 2,975.5, Kenya's FTE of 1,156.2 and Ethiopia with 3,024.6 rank as some of the highest in SSA (ASTI, 2017). However, Brazil's FTE of 5,869.3 and India's FTE of 11,362.8 as given in the ASTI database, depict what the African countries ought to be attaining to enhance agricultural R&D. The quality of the human resource is also reflected in the percentage of PhD graduates in the disciplinary mix. Ghana and Kenya have PhD holders among the agricultural R&D human resources of 45% and 40% respectively. However, Nigeria's is 24% and Ethiopia is only 8%. Though Ethiopia scores rather high on FTE, it however scores low in PhD holders. In countries making reasonable progress and impact in agricultural R&D, the percentage of PhD holders in the human resources mix is higher – for Brazil it is 72.5% and for India it is 77.5% (ASTI, 2017).

A continental study on Agricultural research capacity indicated that out of the 37 countries with a complete set of degree-level data, five countries (Benin, Burkina Faso, Madagascar, Senegal, and Swaziland) recorded shares of PhD researchers of more than 40 percent, while five countries reported shares of PhD researchers of 10 percent or lower (Ethiopia, The Gambia, Guinea-Bissau, Lesotho, and Mozambique) (Beintema and Stads, 2014). The study also found that in spite of the absolute increase in the number of PhD-qualified researchers, agricultural researchers with PhD degrees declined from 25 to 22 percent between 2000 and 2011. For more on agricultural capacities, see also for example, Essegbey and Asare (2014).

Pressure on resources—including loss of secure faculty positions—has deteriorated instructional and research resources and facilities. Improvements in RIs in agriculture and food systems have been recorded in a few relatively large countries (South Africa, Nigeria and Egypt), as reflected by the increase in research outputs. However, investments in most Francophone countries remain stagnant or falling.

In a number of countries, the organisational architecture for R&D is in place, though it remains highly complex and the majority of the potential linkages and instrumental arrangements are underdeveloped (World Bank, 2019). Funding for agricultural research has generally been dependent on national and international sources. Nonetheless, in some contexts, international players remain one of the highest source of funding, especially for operational costs and capital investments, for example, as obtained in the African Centres of Excellence (ACE) programme. Notable international sources include the Bill and Melinda Gates Foundation, the Brazilian and Chinese governments (Chataway et al, 2019).

In addition, the severe fluctuations in yearly agricultural R&D funding greatly “complicate and compromise long-term budget, staffing, and planning decisions, all of which affect the continuity and outcomes of research” (Beintema and Stads, 2014, p.20). These fluctuations in yearly investment levels hamper the advancement of technical change as well as the new varieties and technologies, which invariable negatively affect agricultural research productivity and growth. The greatest fluctuations occur in international funding or funds from international development partners, severely affecting heavily dependent countries. This is because, for example, in many research projects funded by international partners, provision for RIs development are rarely included. As of 2014, countries with the highest degree of fluctuation in yearly agricultural R&D spending were Burkina Faso, Gabon, Mauritania, Sierra Leone, Sudan, and Tanzania (Beintema and Stads, 2014). In contrast, Republic of Congo, Rwanda, and South Africa maintained a stable yearly agricultural R&D expenditure.

Lastly, RI in agriculture has been characterised by poor technology, research equipment and neglected infrastructure (Task force, 2018). However, there are noticeable variations depending on whether the institutions belong to the group where, over the years, there have been neglect, lack of, or inadequate funding of RIs. The institutions which were able to access domestic and external funding are exempt from this group and they have managed to maintain modern and fairly state-of-the art RIs, such as those in the ACE.

ACE is a World Bank initiative to support higher education institutions in Science, Technology, Engineering and Mathematics (STEM), Environment, Agriculture, Applied Social Science / Education and Health. Under ACE I, which was launched in 2014, 22 Centers of Excellence (CoE) in nine (9) West and Central African countries namely Benin, Burkina Faso, Cameroon, Côte d'Ivoire, Gambia, Ghana, Nigeria, Senegal and Togo were included. The second phase (ACE II) was launched in 2018 East and Southern Africa with 24 centers across Ethiopia, Kenya, Malawi, Mozambique, Rwanda, Tanzania, Uganda and Zambia. Crucially, ACE contributes to substantial construction and refurbishment of RIs in HEIs to facilitate teaching and learning in the sciences at higher educational level[xiv]. Given that the ACE Centres run regional post-graduate programmes, these institutions constitute important RI assets for Africa in the respective specialisations of agriculture, health, environment and STEM.

Box 2: The New ACE Project, ACE Impact

On the basis of the success of the initial phase, the World Bank and the French Development Agency (AFD) in collaboration with African governments, launched the Africa Centers for Excellence (ACE) Impact Project in 2018 to strengthen post-graduate training and applied research in existing fields and support new fields that are essential for Africa's economic growth. Currently, there are 43 ACEs (25 new and 18 from ACE I); 5 Emerging Centers; 1 "top up" center in Social Risk Management; and 5 Colleges and Schools of Engineering.

With this new project, the World Bank has increased its total financing for the ACEs to $456 million, including the previous phases – ACE 1 ($165 million) and ACE 2 ($148 million) – which are currently operational. Under the three phases of the ACE programme, 45 universities in 19 countries are implementing 58 ACEs where a total number of 24,000 students are enrolled, including 10,500 at the Masters' level and 2,400 at the PhD level. A total of 34 programs are certified to meet international quality standards, thus showing African higher education can meet global standards. Funds dedicated to research infrastructures significantly contributes to upgrading research facilities in the beneficiary institutions as well as producing high-level graduates.

Source: compiled from https://ace.aau.org/about-ace-impact/

Box 3: Agricultural expenditure - The case in Ghana

In the area of funding, Asare and Essegbey (2016) examine the financial investment and expenditure trends in agricultural R&D in Ghana with emphasis on the Council for Scientific and Industrial Research (CSIR) and the implication for the policies driving agricultural research in Ghana, using ASTI data and conducting in-depth studies on agricultural R&D in the country. Purposive sampling was used to gather data in thirteen agricultural research institutes and five public universities in Ghana. The study revealed that, total public agricultural R&D expenditure had increased by 59% from 42.5 million (2005 PPP) US dollars in 2000 to 67.7 million (2005 PPP) dollars in 2011 and with an average expenditure of 54.1 million (2005 PPP) dollars per year.

The total expenditure by CSIR constitutes about 50% of the total agricultural research expenditure in Ghana. The study however, showed a significant decline in capital investments from 6.7% in 2000 to 0.1% in 2011 of the total government funding. Already a capital investment level of 6.7% was extremely low. For capital investment to come down further to 0.1% indicates a gradual disappearance of that investment component of government funding. This has to be corrected with government funding of capital investment increased to at least 10%. Improvements in this regard will in turn have positive effect on the building or upgrading of research infrastructures

Source: Asare and Essegbey, 2016

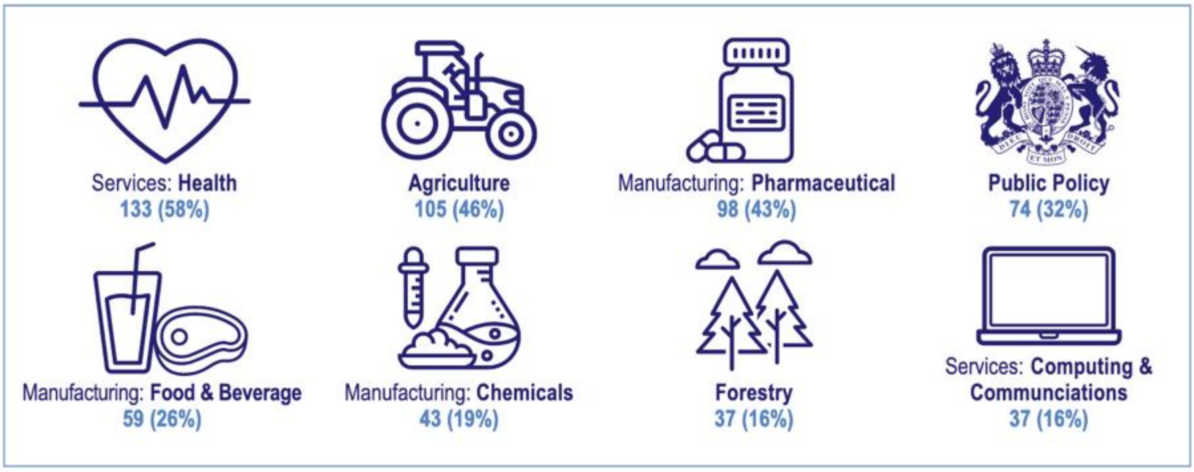
4.3 RIs in Health and Medicine

RI deficiencies in Africa's health and medicine is evidenced by the continent's weak inputs towards the global fight against COVID-19 standing at 0.6% of global contributions (Gwenzi and Rzymski, 2020). South Africa takes the lead in health and medicine research, in Africa as measured by research output, PhD enrolments and completions, and is closely followed by Nigeria (Gwenzi and Rzymski, 2020). North African countries lag behind as they have been, during previous pandemics, unable to carry out research in order to understand the dynamics of infections within their populations (Ibrahim et al, 2020).

Similarly, despite the high prevalence of infectious diseases in Africa, the continent has the weakest contribution to research in infectious diseases (Mbaye et al., 2019). In order to fast-track the process of drug and vaccine discovery, there is a much-needed intervention to establish and deploy adequate physical and virtual infrastructure. Sustainable progress in disease elimination can only be achieved if the most affected countries make robust contributions in terms of understanding disease prevalence and transmission dynamics, diagnosis, drug and vaccine discovery and development. This is improbable in the absence of quality RIs (Sam-Agudu et al., 2016).

As noted earlier, RIs often serve multiple domains with breadth and overlaps across sub-disciplines. For example, RIs in biological sciences[xv] could also serve disciplines such as health, agriculture and food. Similarly, RIs in biological sciences have been shown to contribute to or work with eight economic sectors, excluding research and education (Figure 7). This highlights the importance of RIs to economic growth and development.

Figure 7: Biological sciences, health and food infrastructures contribution to the economy



Source: UKRI, nd, p.63

The landscape of medical and health research in Africa is changing with the establishment and strengthening of some of its medical research institutions. For example, the West African Centre for Cell Biology of Infectious Pathogens (WACCBIP) was established in November 2013 with the commitment of $8 million from the World Bank as part of the ACE project.

Currently, WACCBIP continues to build the infrastructure and partnerships that drive science and innovations in its domain of medical research, focusing on challenges associated with infectious diseases in SSA[xvi].

Box 4: RIs at the West African Centre for Cell Biology of Infectious Pathogens (WACCBIP)

RIs at WACCBIP include four research laboratories, which are optimally resourced for the conduct of cutting-edge research, and these are: i) the Laboratory for Chemical Systems Biology of Infectious Pathogens, ii) the Cell Biology and Immunology Laboratory, iii) the Virology Laboratory and iv) the Molecular Biology Laboratory housing five research groups. They are equipped with certified biosafety cabinets, laminar flow cabinets, workstations and optimised workspaces, microcentrifuges, thermocyclers, -80^{o}C freezers, CO_2 incubators, refrigerated centrifuges, QuantStudio 5 real-time PCR machine, 3-in-1 (absorbance, luminescence and fluorescence) plate readers, fluorescent microscopes, and a gel imager.

There is also access to a BD FACS LSRFortessa X-20 duo with 5 lasers (blue, red, violet and UV; 18 colours/parameters) that can acquire data using either tubes or HTS module and detects up to 20,000 cells per second as well as a high-end Zeiss LSM 800 confocal microscope with Airyscan, a cold room and liquid nitrogen storage tanks within the WACCBIP facility. A recently installed MiSeq sequencer has been of great use in sequencing COVID-19 genomes and in monitoring the dynamics of spread of COVID-19 within the Ghanaian population. WACCBIP also has a “Zuputo” Dell EMC High Performance Computing System that supports bioinformatic analysis. These equipment were acquired using funds mostly from the World Bank through the ACE project and the Wellcome Trust Developing Excellence in Leadership, Training and Science (DELTAS) Africa Programme under the auspices of the African Academy of Sciences’ (AAS) Alliance for Accelerating Excellence in Science in Africa (AESA) initiative, the Wellcome Trust, the UK’s Foreign and Commonwealth Development Office (FCDO)[xvii] and the New Partnership for Africa’s Development (NEPAD).

Individual research groups also receive funds from different international funding bodies such as DAAD-Germany, Grand Challenges Canada, TWAS-Italy, IFS-Sweden, Gates Foundation/ NMIMR??, Royal Society-Leverhulme Trust, Tackling Infections to Benefit Africa (TIBA) partnership, Cambridge Africa Partnerships for Research Excellence (CAPREx) -Alborada, Willowcraft Foundation, National Institutes of Health (NIAID-NIH), and Medical Research Council. WACCBIP also serves as a hub for the West African Network of Infectious Diseases ACEs (WANIDA). This network is funded by Agence Française de Développement (AFD) and Institut de Recherche pour le Développement (IRD). And is made up of six ACEs in four West African countries (Ghana, Nigeria, Burkina Faso and Guinea).

On the specific case of fighting the COVID-19 pandemic, a number of African institutions are involved in research for vaccines and therapeutics. For example, Ethiopia's Centre for Innovative Drug Development & Therapeutic Trials for Africa (CDT-Africa), a World Bank financed Africa Center of Excellence based at the University of Addis Ababa has joined a global COVID-19 Clinical Research Coalition of over 70 institutions from over 30 countries. The coalition "aims to accelerate desperately needed COVID-19 research in those areas where the virus could wreak havoc on already-fragile health systems and cause the greatest health impact on vulnerable populations."[xviii] CDT-Africa is also working on two clinical trial protocols related to what is considered a promising treatment and one related to health system improvement relevant to the COVID-19 pandemic. Participation in the COVID-19 trials is an indication that African medical research centres are not altogether oblivious to the global fight against the pandemic. Still, the fundamental issue relates to the extent to which Africa's capacity in medical research can result in cutting-edge research leading to inventions and innovations that are in line with global standards.

In spite of the advancement in medical research in Africa, there are gaps in RI in health and medicine on account of the following:

1. *Insufficient funding:* Health and medical research in African countries relies heavily on foreign bodies for funding (Chataway et al, 2019), despite having the greatest global burden of infectious diseases in Africa. One consequence of the over-reliance on external bodies is their dominance of the research agenda and focus, which might not directly align with the needs of African countries. Furthermore, some of these bodies lack provision for investment in facilities and equipment which are the prerequisite for sustainable research. As a consequence, African countries remain at the mercy of these external bodies for funding research for diseases which are most prevalent in Africa.

   The lack of comprehensive funding systems by African governments due to limited resources and low prioritisation exacerbates the situation. In the few cases where local funding exists, they are often poorly sustained and inadequately publicised. Corruption is another major challenge that affects the availability of funding (both those from international funders and African governments, where such exists) for investments in RIs.

   The advanced specialised equipment required for health research necessitates a reasonable amount of financial investment to ensure adequate maintenance. In some instances, expatriates are required to fly in periodically to service RIs. Failing which, these expensive equipment are left unused, resulting in deterioration. The funding issue also impacts on human resource (personnel) as funds are needed for African researchers to pursue advanced degrees and to attend training courses on the use of specialised equipment needed for health research. This contributes to the low number of researchers per million in SSA (UNESCO, 2015, 2019). Furthermore, insufficient remuneration discourages highly skilled African scientists from remaining in the continent and those in diaspora from returning home, driving brain drain (discussed later in this section).

In terms of VRIs, many African scientists are compelled to raise personal funds for purchasing equipment, as basic as a personal computer, to execute research effectively. Software needed for word and data processing and statistical analysis, even access to certain online literature that require paid subscriptions, are often lacking in HEIs.

2. *Inadequate RI:* The majority of African HEIs continue to struggle with inadequate RIs and VRIs (as noted in Figure 5). This is a direct consequence of insufficient local funding, especially where external funding is lacking in these institutions. Laboratories in these African institutions are poorly equipped, suffer from inadequate scientific equipment to carry out good quality research. In the few cases where better facilities exist, they tend to be obsolete and substandard, and lack technical expertise to operate them (Gwenzi and Rzymski, 2020).

   Admittedly, from our review of the literature and the empirical evidence gathered, a few African HEIs maintain sound RIs.

3. *Publications:* Virtual libraries are now the order of the day. Access to bibliographic databases is crucial to research, teaching and learning in HEIs. Access is however limited in many African HEIs. Usually access is secured through partnerships with foreign educational or research institutions. In the scientific disciplines, ensuring the availability of current publications is an enabler of good research, and helps to prevent wasteful replication of research efforts. Low publication quantity and quality is an indirect effect of poor research capacity. In addition, emphasis on quantity of research output, rather than quality results in poor quality scientific contributions that are unable to attract funding to build capacity in African institutions. Figure 2 above presents the gaps in the scientific equipment, a vital RI that supports publications.

4. *Unreliable electricity supply:* A major constraint to the development of VRIs in SSA is access to reliable electricity supply (IEA et al, 2019). SSA has the lowest household electrification rate in the world. There is significant disparity in electricity access between rural and urban households. In addition, low quality of electricity service characterised by long, and in most cases unplanned, power outages and high cost of electricity, hinders research and innovation in HEIs. Electricity access, reliability and cost remains a major challenge in several African countries (BCSD, 2019), and impedes good research. Electricity supply is crucial in developing VRI and where it is epileptic, there is an over-reliance on alternative sources of energy which are very expensive and often unsustainable. Empirical evidence gathered in this research corroborate these insights that for about 50% of the time, HEIs in SSA face unreliable electricity (see Figures 2, 4 and 6 above).

5. *Limited institutional collaboration:* There is limited inter-institutional collaborations between and within African institutions resulting in unnecessary competition and detrimental duplication of efforts which negatively impacts the optimal use of available labs and facilities. It is important that the focus needs to shift to cooperation and collaboration, joint research, co-location and sharing of RIs as narrated ain Box 5. Although our empirical indicate that institutional collaboration occurs, this currently stands at 60% (see Figure 6), indicating ample rooms for improvements in the areas of co-location, sharing of resources, co-funding and co-management/governance of RIs (see Figures 2, 4 and 6).

   It is imperative that the often inequitable north-south collaborations that tend to expose African scientists to unfair roles and benefits are actively and systematically addressed.

Box 5: Example of Colocation of Virtual RI in HEIs The UK Data Service (UKDS) is an Economic and Social Research Council (ESRC)-funded infrastructure partnership between Essex, Manchester, Edinburgh and Southampton universities, University College London (UCL) and Jisc[3]. It provides training, support services and access to major UK government-sponsored surveys, cross-national surveys, longitudinal studies, UK census data, international macro-data, and business and qualitative data. Source: UKRI, nd, p.101

6. *Brain drain, brain gain and brain circulation:* Brain drain and the need for brain circulation constitute major issues in RIs in SSA (see Figure 6). Literature abound on mobility of African academics, their push-and-pull factors and their record and pattern of low return—along with the implications.

   Brain drain – the emigration of skilled professionals – remains a major challenge to research and development in Africa, with a greater proportion are HEI researchers in STEM with Ghana, Ethiopia and Nigeria being the top émigré countries (Ukpokolu, 2020). Brain drain of HEI researchers has been partly sparked by inadequate RIs. Bashour (2013) contends that "the inadequate RIs, laboratories, data processing centres, biobanks and other brick and mortar needed for research" are lacking in Africa and this push researchers out of the continent in a bid to pursue their research careers. A recent quantitative study on RIs in Africa revealed that over 70% early career researchers had a strong appetite to migrate to Western countries for research purposes, while 35% migrated for short term research purposes outside their home countries (Makoni, 2018).

   Increasingly these academic diaspora are considered as major potential assets in advancing research in the continent through appropriate interventions—to enhance

[3] Jisc provides digital solutions for UK education and research, https://www.jisc.ac.uk/about

brain circulation. That noted investing in both physical and virtual RIs and systems in a sustainable manner can not only help retain scientists at home but also help to attract the intellectual diaspora and other expatriates to Africa.

7. *Human resource factors:* Lack of mentorship and peer support opportunities, inadequate digitalisation and digital skills among African researchers hampers progress in , effective communication and dissemination of research findings and outputs, and collaborations that are underpinned by virtual RIs (see Figures 4 and 6).

   Qualified and competent scientific researchers are essential for the conduct and production of quality and viable research. In terms of human resource capacity, the overall research capacity has increased in recent years. For example, the number of researchers with PhD and MSc has increased in the majority of African countries.

Although discussed under health and medicine, it is important to note that some of these challenges are cross-cutting and relate to other sectors and need to be addressed for effective functioning and exploitation of RIs for socioeconomic development and transformative change.

4.4 RIs in Science, Technology, Engineering and Mathematics (STEM)

The deep-rooted challenges arising from Africa's weak research system is not peculiar to health, medicine and agricultural sciences. The challenges cut across other STEM fields. African ministers participating in the Partnership for Applied Science, Engineering, and Technology (PASET), in March 2014 agreed in Kigali, Rwanda, to adopt a strategy that uses strategic investments in S&T to accelerate Africa toward a developed knowledge-based society within one generation.

PASET, an initiative of the World Bank, supports efforts by African governments and their partners to strengthen the role of applied science, engineering, and technology in the development agenda. According to Makhtar Diop, World Bank's Vice President for the Africa Region:

> Higher education is now front and center of the development debate – and with good reason. More than 50 percent of the population of sub-Saharan Africa is younger than 25 years of age, and every year for the next decade, we expect 11 million youth to enter the job market. This so-called demographic dividend offers a tremendous opportunity for Africa to build a valuable base of human capital that will serve as the engine for the economic transformation of our continent. To be more competitive, expand trade, and remove barriers to enter new markets, Africa must expand knowledge and expertise in science and technology (Blom et al, 2016).

A World Bank report that examined the supply of, and demand for, skills, education, and research in STEM for Africa's socioeconomic transformation and poverty reduction under the aegis of the PASET highlights two key points, the need for SSA to 1) increase both the quantity and quality of its research output and 2) address the low research output in STEM (Blom et al, 2016). These gaps are nothworthy. However, despite the many challenges confronting Africa HEIs and R&I ecosystems, some of which are discussed in this report, SSA has greatly increased both the quantity and quality of its research output (Ali & Elbadawy, 2021) with recent evidence indicating that the global contribution has risen from the previous estimate 1% to about 7.6%[xix]. South Africa, Egypt and Nigeria remain the leading countries in research outputs with growth rates varying across the countries.

Clearly, Africa has more grounds to cover to build the required capacity and capabilities to enhance the continent's STEM. Though some progress has been made in the last one to two decades, there is need to accelerate efforts in strengthening capabilities. RIs have an important role to play in this regard. While African governments are encouraged to partnerships with development partners in building RIs, ultimately the onus is on the governments to invest in RIs for STEM research and education.

The intense pressures on resources have led to a deterioration of instructional and research facilities and resources leading to reduced morale and decrease in research output (Zeleza, 2018). Inadequate RIs continue to undermine African universities' capacities to conduct viable scientific research and adopt ICT for teaching and learning. Investment in RI is urgently needed on many fronts. Besides South Africa and a few countries in North Africa (Egypt, for example), universities in Africa have experienced acute shortage of financial resources (Mokwunye, 2010). A 2019 World Bank study on Ghana, Senegal, Cote D'Ivoire, Malawi and Mozambique found that scientific laboratories for agriculture and STEM disciplines were grossly inadequate in many African universities. The study also revealed that there was the need for the construction of new facilities and renovation to enhance ICT in teaching and research. ICT infrastructure, including internet bandwidth, servers, computers and helpdesks were unavailable in most universities (World Bank, 2019).

Furthermore, the use of analytical tools in assessing agri-food sector skills and feedback into research were lacking. The report also highlighted poor staff incentives, weak support systems and excessive teaching load as factors which further hampered research efficiency, contributing to low research output. Many agricultural institutions and agencies face several challenges in terms of the scope and quality of their infrastructure. This includes basic needs "such as office space and supplies and access to computers, software, the internet, research publications, and even water and electricity and […] include laboratory space and equipment, farm equipment and vehicles, and so on" (Beintema and Stads, 2014, p.6). In addition, majority of the research facilities are outdated, ill-equipped, or non-functional.

These findings on the gaps in RIs, which are essential for supporting STEM are important and require urgent attention. As we know, STEM plays a vital role in innovation, which in turn is critical to progress in socioeconomic development – employment and job creation, education and other sectors. The findings of this research (see Figures 2 to 6 above), provide empirical evidence that support the insigiths from literature and preceding sections.

4.5 Policies, Regulations, Standards and Frameworks on RI and HEIs in Africa

The Continental STI Policy Environment

Policy is a crucial instrument for achieving developmental goals. STI policies have been promulugated over the years in African countries and at the sub-regional and continental levels with a view to strengthening the education, research and STI environments. At the continental level one may go back in history to the efforts at committing African nations to concrete STI-focused programmes and initiatives to enhance socio-economic development. There was the Lagos Plan of Action of 1980 and there was the Consolidated Plan of Action of 2003 signed in Maputo.

Of recent, the Continental Education Strategy for Africa (CESA 16-25) and the Science, Technology and Innovation Strategy for Africa (STISA 2024) were developed as the key African continental policies with the primary goals of facilitating the achievement of the AU 2063 Agenda through education and STI respectively. CESA (16-25), for example, notes that the “quality and relevance of university education have emerged as serious concerns of the sector for some time now. [And that] Post-graduate education remains underdeveloped and its contribution to research and innovation remains minuscule” (AUC, 2016, p.19). STISA 2024, with a mission to “accelerate Africa’s transition to an innovation-led and knowledge-based economy” however places a sharp emphasis on HEIs and STEM with the goal of harnessing STI to build a knowledge economy in Africa.

STISA 2024 has six key areas with policy directions to the AU member countries anchored on four main pillars namely: (i) building and upgrading RIs, (ii) enhancing professional and technical competencies, (iii) promoting entrepreneurship, and (iv) providing an enabling environment for STI development. STISA 2024 therefore provides the framework for formulation and implementation of STI policies in Africa. These noted, the realisation of this goal and the extent to which these countries can build resilient science systems depends to a large extent on their RIs.

ECOPOST

At the African sub-regional level, the same recognition of STI policy relevance is manifested. For example, in West Africa, the ECOWAS Commission in 2012 adopted the ECOWAS Policy on Science, Technology and Innovation (ECOPOST), which provides a framework for the member countries to elaborate their policies and programmes on STI. ECOPOST encourages member countries to, among other objectives, increase their Gross Expenditure on Research and Development (GERD) to at least 1% (which is in consonance with the continental strategies); create a national fund for STI to enable researchers to work on research priorities of the country; equip research laboratories including with ICTs; facilitate the dissemination of modern IT infrastructure to facilitate teaching, training and research; and promote collaboration between the knowledge institutions and industry in the country.

ECOPOST responds to the expectations of a region aspiring to advance beyond the developing country status. It addresses development challenges in the key sectors of agriculture, health, environment and education. To achieve the aims and objectives of ECOPOST, the ECOWAS Commission also developed a 10-point strategic action plan which came into effect in 2013. These are, namely: strengthening the institutional framework for the development of STI policy and associated action plans; strengthening the scientific and technological institutions financial capacity; strengthening human and technical capacity in S&T; development and transfer of technology; popularization of research results; promotion of scientific and technological culture; local knowledge and intellectual property protection; involvement of the private sector for S&T development; development of environment conducive for scientific and technological research creativity; regional and international cooperation; data management and indicators elaboration; and promotion, mainstreaming of S&T in sectorial policies.

However, the key challenge remains implementation of the policies and the committal of resources to carry out the relevant activities to attain the goals and objectives stated in ECOPOST. At the level of member countries, greater efforts need to be made for implementation in alignment with national priorities and policy agenda. This noted, it is encouraging to point the extent to which member countries have established ministries to oversee the portfolio of STI.

STI Institutional Frameworks

With a sole ministry for STI, Nigeria stands out in respect of defining an institutional framework for STI policy formulation, implementation, monitoring and evaluation. Other countries have a ministry for STI either in combination with environment or education. The Nigerian Science, Technology and Innovation policy was formulated and approved in 2012 by the Federal government to transform the country's socio-economic and technological development. The establishment of National Research and Innovation Council (NRIC) is one of the important implementation actions carried out in relation to the STI policy. The Council sets R&D priorities, coordinates STI activities and facilitates fund-raising to support innovative activities. The policy also outlines Nigeria's commitment to at least 1% of GDP to R&D through the establishment of the National Research and Innovation Fund (NRIF) though that figure currently stands at c. 0.22% (Essegbey et al, 2020).

In addition to oversight functions, ministries in various ECOWAS member countries have formulated specific STI policies or plans. For example, Benin formulated the Higher Education and Scientific Research Development Plan (2013-2017), which was adopted in 2014, with the vision that by 2025, Benin would have a sub-sector of Higher Education and Scientific Research, which provides qualified human resources and research results adapted to national development problems (Essegbey et al, 2020). Similarly, Burkina Faso has formulated the National Scientific and Technological Research Policy (2013-2025) highlighting priority areas for research and the aims of linking research to industry. Senegal, although without an explicit STI policy, has adopted the "Plan Senegal Émergent" (PSE), which provides the framework for economic and social development by 2035 on three pillars namely: 1) the structural transformation of the economy; 2) the promotion of human capital; and 3) good governance. Even though there currently are no specific STI-focused policies, Senegal is implementing STI-related programmes under the PSE. For example, significant investment is dedicated to the acquisition of laboratory equipment, a super intensive parallel computer and the construction of the City of Knowledge for the promotion of scientific culture (Essegbey at al, 2020).

Liberia's Ministry of Posts and Telecommunication has formulated the National ICT Policy (2018-2023) that defines policy goals, objectives and strategies to boost ICT applications and digitalization in the country. Given that the primary focus is ICT, it is not the conventional STI policy. However, Liberia has established the Liberia Innovation Fund for Entrepreneurship (LIFE), which became operational in 2015 and it is one of the key programmes initiated to foster innovation and entrepreneurship in the country. However, the strategies for research and defining the institutional arrangement for driving research remain to be better amplified in LIFE (Essegbey et al, 2020).

The North African region also shows strong efforts in building RIs for the respective countries. Egypt's Agricultural Research Center (ARC), which operates under the auspices of the Egyptian Ministry of Agriculture and Land Reclamation, serves as the research and development arm of the Ministry and focuses on conducting applied research to produce technologies and innovations for increased productivity in the agricultural sector. RIs are however spread in the universities and the research centres in Egypt. For example, the American University in Cairo has established the Science and Technology Research Center, which conducts a variety of nanoscience and technology-oriented projects. Egypt's Atomic Energy Authority (AEA) is one of its leading research establishments with some nuclear RIs and a capability to contribute to nuclear medical health research (Iliopulos and Boyd, 2019).

Other North African countries have their own respective research agenda with the required RIs and operating under prescribed government ministries. In Algeria, the Ministry of Higher Education and Scientific Research oversees research establishments that include 50 universities, 20 university centres and 10 research institutes[xx]. The Morocco Ministry of Higher Education and Scientific Research coordinates research, implements the Moroccan Innovation Strategy and supports research in advanced technologies and the development of smart cities in Frez, Rabat and Marrakesh[xxi].

The South African Policy Dynamism

The Southern African region provides an illustration of how STI policy formulation and implementation have contributed to the present science systems, with South Africa representing a good example of the dynamism in the region. In 1996, South Africa formulated the White Paper on Science and Technology with focus on three pillars of investment: (i) innovation; (ii) science, engineering and technology, emphasizing human capital development and transformation; and (iii) creating an effective national S&T system.

The progression in STI policy formulation in South Africa was the National R&D Strategy for South Africa published in 2002. It elaborated key, recommendations including the importance of scientific instrumentation in advancing research, economic growth and human capital development. Other priorities outlined include: the importance of modern, well-maintained equipment as a pre-requisite for high quality research; emphasis on the point that equipment has considerable economic impact, particularly in the manufacturing sector; and that the use of equipment in the educational sector as a key success factor in nurturing curiosity-driven research, and developing the requisite skills for undertaking world class research and supporting the advancement of modern industry (DST, 2002).

In 2010 South Africa produced another relevant policy – the Research, Development and Innovation Infrastructure Funding Framework. The focus on funding is exemplary as funding is one of the key ingredients usual missing in STI policy implementation. The framework identified five investment areas namely: (i) scientific equipment; (ii) high-end infrastructure; (iii) specialised facilities; (iv) access to global infrastructures; and (v) cyber-infrastructure (DST, 2010). The last two investment areas are prerequisites for participation in global science, enabling South Africa’s participation in cutting-edge scientific research projects such as the Square Kilometer Array (Ramoutar-Prieschl and Hachigonta, 2020).

In 2016, South Africa launched the South Africa Research Infrastructure Roadmap (SARIR) which provides a framework for the delivery of RIs necessary for a sustainable NSI. This roadmap articulates the commitment of the South African government to RI development in the country. The investment in SARIR reflects a deep understanding of the importance of RI as a critical enabler for undertaking excellent research (Chataway and Daniels, 2020). The roadmap identifies 13 potential investment areas of interest in RI, classified according to thematic areas (Ramoutar-Prieschl and Hachigonta, 2020). Clearly the dynamism of the R&D and STI policy cycle has impacted on the strength of the South African science system. The White Paper (WP) on STI, developed in 2019, spells out the long-term policy approach of the STI sector. The WP on STI emphasise the core themes of (i) inclusivity (ii) transformation and (iii) partnerships. In addition, the WP expands the investment in RIs, cyber-infrastructure and access to global research facilities (Ramoutar-Prieschl and Hachigonta, 2020). This helps to illustrate the commitment to research and STI for national development.

An important initiative in South Africa currently being implemented is the creation of an elaborate framework for monitoring, evaluation and learning to enhance the NSI. The National Advisory Council on Innovation (NACI), which prepares the South African STI Indicators, in collaboration with the relevant institutions features a wide range of indicators including patents granted to South Africans, trends in business investment in R&D, South

Africa's Global Competitiveness Index, Human Development Index and venture capital investments.

STI Policy Frameworks in Africa

In concluding this section, we note that policy frameworks on research and development have witnessed some level of change in recent years. These changes are linked to the establishment of new bodies to manage and fund research or policy frameworks that mandate investment in capacity. Some of the key policy frameworks include national STI policies by various governments, and the creation of ministries of S&T or STI such as the Ethiopian Ministry of Science and Technology (2013). Other changes include the development of strategies, for example, by the Kenyan government (2010), the Emerging Senegal Plan (2014), the South African Research Infrastructure Roadmap (DST, 2016), and others.

The major concepts of internationalisation, research relevance to socio-economic needs, and human capacity building are core concerns in national research agendas across Africa. These issues are similar, for instance, when compared with the German Research Infrastructure (GRI) roadmap. However, unlike the GRI roadmap, which follows EU Roadmap, the RI in African countries are more fragmented and do not necessarily follow the African Union STISA 2024. The development of STI in Africa requires the upgrading of science laboratories and the establishment of world class STI infrastructure. This includes research and innovation facilities such as laboratories (for teaching, engineering and clinical trials), teaching hospitals, ICT equipment and infrastructure, Innovation Spaces, Living Labs and NRENs.

It is vital that existing physical and digital infrastructure and resources are leveraged and networked to increase utilization efficiency at national and regional levels and reduction in maintenance and operating costs through shared services. NRENs will facilitate coordinated collaboration by education and research institutions between one another as well as with Innovation Spaces and Living Labs, thus strengthening both the overall Research and Innovation Ecosystems and the scale and quality of training and support available to entrepreneurs and other innovators (AUC, 2014). The idea of the continent producing its own scientific equipment has also floated.

At the continental level, the establishment of the African Observatory for Science, Technology and Innovation (AOSTI) in Malabo, Equatorial Guinea was intended to provide a robust framework for monitoring and evaluating Africa's STI. Efforts at implementing programmes to this effect include the ASTII Survey conducted in two phases: 2007-2010 and 2010-2014. This, however, proved unsustainable as the pilot was supported by external funders and subsequently did not find support from member countries.

Africa needs to take the fate of its RIs, research, STI seriously and invest in the entire policy cycle i.e. formulation, implementation, monitoring and evaluation, and governance to realise the dream of driving on the wheels of STI to socio-economic advancement.

Box 6: RIs organisation, policies and regulations at national level – the case of South Africa

In South Africa, RIs for STI is organised at three levels of engagement namely "(i) government and policy level; (ii) the funding agency level; and (iii) the implementation level, at research-performing institutions" (Ramoutar-Prieschl and Hachigonta, 2020, p.5). RIs for STI in South Africa's HEIs are characterised by "unequal funding; skewed demographic profile of students and staff; inadequately skilled or trained academic staff to lead research projects and/or supervise postgraduate students; institutional histories; varying levels of support from industry as well as regional and local communities surrounding universities; and varying impacts of the evolving social discourses and national policy priorities" (Ramoutar-Prieschl and Hachigonta, 2020, p.11). Efforts to rebalance the ecosystem must adopt a systems of innovation approach that takes into account gaps across multiple sectors, systems and societies.

In summary, gaps in policies and regulations related to RIs, remain acute in SSA. With respect to the lack of implementation of government policies, evidence from survey date shows that this stands at 54%. Addressing this gap is important for many reasons. On the positive side, Figure 5 shows the adequacy of RIs as 39%[xxii], whereas the inadequacy of RIs stands at 45%[xxiii]. Combined with responses on neutral (15%), this rises to 60% level of inadequacy. The formulation and effective implementation of policies and regulations on RIs can help address these gaps.

4.6 Cross-cutting issues and implications on RI in Africa

In this section, we discuss six cross-cutting issues that has emerged from the preceding sections – gender and inclusivity, human resources and capabilities, the role of private sector, governance and sustainability. These cross-cutting themes are essential to strengthening science (including research and innovation) systems. They highlight some of the areas that research and (policy) interventions on RI should focus on.

4.6.1 Gender and equity dimensions, access, gaps and implications on RI in Africa

Gender remains a critical issue in STEM, agriculture, and health sciences and medicine. Women make up more than 50% of Africa's population. However, they are less represented in higher education, especially in science disciplines where the numbers are fewer. Studies of women in sciences have all ascertained the lower numbers of women in science disciplines in general although there are minimal variations across countries. Although the number of female students studying science courses have increased over the years, gender disparity continues. Hafkin (2016) found that while women made up 45% of university students in Rwanda, their representation in engineering was only 31%. This finding reflects similar situations in other countries (Hafkin, 2016).

In Kenya, female graduates in engineering, manufacturing and construction in 2012 comprised only 5.9% of students while the rate for female students graduating in all science programs was 9.5%. Uganda has a relatively high female enrolment in science (33%) and female researchers (40%). In Kenya, women account for only 27% of students in STI fields. In all the four countries studied, women's representation was relatively high in health sciences than in agriculture and STEM. Gender disparities were not only present in enrolment but also in faculty members (researchers). In Kenya for example, 80% of faculty members in science and engineering were men. Absence of programmes aimed at the recruitment and retention of female scientists, "coupled with an undefined career path, and the absence of mentoring programmes within institutions to provide professional support", increases the difficulty to attract and retain female scientists (Muthumbi, 2015, p.2).

Major challenges to women's representation in science include the limited female role-models (as the majority of science heroes and researchers are men), socio-cultural factors that continue to confine women to domestic work, the conceptualisation of gendered career, misconceptions about the masculinity of science research and career, weak support for female scientists career advancement, domestic roles which affects women's research output, male bias in curriculum, textbooks and pedagogic practices, sexual abuse and harassment from male lectures and supervisors and gaps in research governance and administration (Muthumbi, 2015; Hafkin, 2016; and Tiedeu, 2020). Sexual harassment for example hinders women from accessing libraries, laboratories and study spaces, which impacts on their ability to fully participate in the knowledge society, thereby affecting their research output (Hafkin, 2016).

Female academics and researchers tend to have a smaller number of published papers than men due to women's multiple roles (in the domestic sphere and as researchers) (Hafkin, 2016). According to Muthumbi (2015) the policies and regulatory frameworks have a role to play. For example, gender-friendly policy frameworks – that enhances the provision of childcare facilities at the workplace or promotes ease of career re-entry following a break to start a family – contribute to the retention of female scientists in careers and reduces the risk of widening the gender gap in health research. To address gender disparity, a number of countries have formulated policies to increase enrolment rates in science programmes. Almost all African countries have enacted laws and frameworks, either in their respective constitutions or ratification of international instruments and laws calling for various forms of affirmative action to promote gender equality but the challenge of implementation remains.

The Southern African Development Community (SADC) gender policy, the Gender Equality Strategy for CESA 16-25 and the Nairobi Declarations are examples of policies which entail measures to promote gender equality. However, these policies and declarations do not specifically address the gender issues, gaps and challenges of female researchers in science. The majority of STI policies in SSA, including STISA 2024, do not effectively address gender inequality in science. The few programmes and policies which specifically speak to the gender gaps in science – for example, Africa Consultative Group on International

Agricultural Research (CGIAR), African Women in Agricultural Research and Development (AWARD), the Ethiopian National STI Policy in 2012 – are weak on implementation (Muthumbi, 2015). Hafkin (2016, p.3) in studying gender gaps in science in Ethiopia, Rwanda, Kenya and Uganda found that "constitutional and policy commitments to gender equality and inclusion often fell short either in omissions in sector policies, in program and project implementation or through deference to cultural/religious laws and practices on divorce, inheritance, property ownership that uphold patriarchy".

In this research we find that there is a significant gap in literature on the intersectionality of RI and gender in science, technology and agricultural research. In particular, studies that interrogate the gender implications of RIs in Africa, its connections with women's career progression and output, or migration is lacking. One reason for this gap is because scarce facilities, including research facilities place the dominant and powerful gender (men) at an advantage over the vulnerable gender (women) which could reduce their interest in scientific research.

It is important to deepen our understanding in ways that gender power dynamics plays out in RIs governance and the implications on the female scientist's research and academic career. Efforts have generally focused more on S&T education, than on employment. In some regions (such as such as North Africa), little has been done to address the hurdles that women scientists and engineers face. One area of gap is the paucity of data on women's progress in science. It is difficult to assess how much progress has been made globally, particularly with regard to women's employment in STI in Africa. There is a dearth of data on women researchers, their outputs or innovations. Awards have been designated for female innovators during which hardly any competitors emerged.

Accessibility – empirical evidence from the research data

Issues around marginalised groups appeared to be the code that influenced accessibility followed by HEIs and R&D. This suggests that the respondents considered marginalised groups (disabled and females) to be affected most by access. Marginalised groups in this context refer to females, persons with disabilities and rural communities. The issues regarding access include representation in STEM courses, physical challenges to access RIs by those with disabilities, the disparities between rural and urban areas, and gender disparity in leadership or careers.

Interviewees and focus group respondents noted the importance of physical access to facilities (library, laboratories) and expensive high-end equipment in HEIs and R&D insitutions across SSA. To this end, it may be necessary to conduct audits of human resource and equipment to establish capabilities, ensure availability of funding, and increase the number and quality of R&D facilities.

Access challenges

From the interviews and focus group discussions, accessibility and maximum utilisation of RI in SSA has a range of challenges including: i) an insufficient number of computers, high cost of broadband and poor connectivity (BCSD, 2019), especially in the rural areas; ii) culture and religion where patriarchal societies prevail and gender disparities are wide spread. Results further indicate that although steps are being taken (such as structuring buildings and other physical facilities), certain groups, including the blind, deaf, rural folks, and females, still remain excluded or have limited access, leading to disparity in RI access.

Furthermore, long bureaucratic processes and administrative procedures to access equipment and other RI components were also noted. This leads to delays in the purchase, access, and underutilisation of RI. Researchers often work through informal networks due to limiting institutional RI processes. Institutional and national security were also identified as hampering access to and optimum utilisation of RI in parts of SSA.

Furthermore, the absence of trust was also mentioned as a disincentive to sharing. Joint acquisition and joint management with functional partnerships that would enable institutions to acquire and share equipment and facilities are often either lacking or hampered as a consequence spending hard-won resources rather inefficiently and imprudently.

Recommendatins for improving inclusivity and access are presented in Section 6.

4.6.2 Human resources, capacities and skills

From the definitions above, RIs extend beyond tools for research to also include issues of human resource, skills and capacity for research. The capacities and skills of researchers – faculty and PhD students – are therefore relevant in the discussions on RIs. There are indications that weak or poor RIs contribute to brain drain of faculty. Likewise, discussions on PhD programmes are key to research capacity. What is less known however is the extent to which weak RIs influence student's decisions to enrol in PhD programmes and their implications on national research agenda. This research seeks to unpack these questions for deeper insights.

A study by DAAD and the British Council to examine research capacity and doctoral training in five African countries (Ghana, Senegal, Nigeria, Kenya, Ethiopia and South Africa) in 2018 revealed that higher education programmes, particularly PhDs, as being carried out in universities determined mainly by "institutional mission, department or faculty level capacity in terms of human resources, and to a lesser extent also the national research or national development agenda" (DAAD and British Council, 2018, p.18). The study indicated that Ethiopia particularly had a big gap between PhD research topics and the broader institutional/national research agenda while in Ghana, university leaders were divided on the merits and feasibility of aligning institutional research activity to a set national agenda. The Nigeria report also stressed PhD programmes as unrelated and non-responsive to the social and economic challenges of the continent (Akudolu and Adeyemo, 2018). The report revealed an inadequate understanding of the alignment between national research agenda and PhD programmes, which were rather based on departmental discussions often based on the availability of lecturers and relevance to the advancement of knowledge.

On the other hand, the Nigerian study indicated that personal interests, needs and career goals influenced the research goals of PhD students, and not the national research or development agenda. This was partly due to the fact that Nigeria as a country lacked any national research agenda that guided HEIs until 2016 when the National Research and Innovation bill was passed. The bill provided for the creation of the National Research and Innovation Council (NRIC) to establish priorities for research, innovation and development in line with national priorities for economic, social and political development. This obviously demands national institutions to set research priorities that are relevant to meet the developmental needs of the nations. The impact of the NRIC on research and development in higher educational institutions is yet to be studied. The study also found poor funding and collapse of RI as major challenges which also hampered research output in Nigerian universities.

Overall, there has been a considerable increase in the number of PhD enrolment in Africa, however, there is also a sharp decline of master's degree conversions into PhD studies. The extent to which these trends are influenced by RI requires further exploration. Ethiopia has the highest PhD programmes in STEM (64%), followed by Ghana (57%), South Africa (49%), Senegal (46%) and Kenya (25%) (DAAD and British Council, 2018). This increase is attributed, in part, to the exponential increase of private universities and the moderate increase in teaching and learning infrastructure (including research). Although the duration of most PhD programmes is 3 years, the average completion time is 6 years which indicates that PhD programmes take longer in Africa.

There are scarce studies on why PhD studies take longer in Africa and the roles that RI play in the completion rates. A report by the Higher Education Research and Advocacy Network in Africa (2014) highlights a low and inconsistent PhD capacity in Africa, which is marked by poor RIs, lack of qualified lecturers and poor funding of higher educational institutions. Till date, Africa remains the continent with the lowest rates in producing PhD graduates due to weak research systems and infrastructure to support STEM education. This has significantly contributed to high number of Africans migrating to Western countries to pursue PhDs.

International collaboration offers the African researcher the greatest opportunity to access high technological research tools and equipment to conduct research. Accordingly, international collaborations for research account for 60% of research output while intra-regional collaboration account for only 15% of the research output in Africa (DAAD and British Council, 2018). Wild (2018) contends that a good number of African researchers collaborate with international researchers because of absence of research equipment for basic research at home. Weaknesses in RI therefore contributes to the weak research coordination and collaboration among researchers in Africa, resulting in reduced opportunity for the continent to enhance research output. Thus, HEIs and research centres are not able to maximize their potentials in research and optimise their outputs of their faculty and PhD students. Wild (2018) opines that while international collaborations may seem a significant choice for African researchers to mitigate the challenges of poor RI on their researchers and appear ‘harmless’, they are often tied with obligations of funders and their scientific agenda, which is often not in lock step with continental and national research agenda.

In similar vein, Ndofirepi and Cross (as cited in Tijssen and Mbula 2018, p.393) argued for an African-centred paradigm “by providing a space for African peoples to decipher their own experiences on their own terms, philosophies and constructions, instead of being directed through a Eurocentric lens”. Calling specifically for a reconciliation of research with socioeconomic interest, they argued that this can hardly be achieved if African researchers continue to depend on external funding and internationally led research collaborations. This is because external funding, which accounts for a greater percentage of research funds in Africa often forbid RIs development.

Research competence (qualified researchers) in Africa has contributed to the low research output. The global average for scientific researchers per one million inhabitants was 1,094 in 2014. In Sub-Saharan Africa however, the number of researchers per one million inhabitants stood at 87.8 (UNESCO, 2014). This number indicates an acute shortage of researchers in the continent. This is highly below the threshold when compared with Asia (166.5) and Latin America (434.9)[xxiv]. The lack of RI in Africa invariably impacts its ability to produce researchers when compared with the high-quality RI in Asia and Latin America.

4.6.3 The role of industries and private sector in SSA’s RIs development

In general, HEI engagements with the private sector in the conduct and implementation of research projects have been uneven. There is a weak link between university research priorities and industrial needs. However, new forms of partnerships or engagements are beginning to emerge through collaborations for industrial trainings as part of academic work especially in the fields of ICT, agricultural and health sciences. Research, especially in health and medicine, is typically very collaborative and multidisciplinary, creating avenues for access to high-tech physical and virtual infrastructures between academia and industry, where such collaborations exist. While the adequacy of public funding is a crucial condition, there are a number of concrete programmatic initiatives that could be taken by the higher education and research institutions themselves including improvements in the management of research, identification and concentration on "areas of strength," and pooling resources with other institutions (Sawyer, 2002), effective information exchange and collaboration (Kasprowicz et al., 2020).

The exponential growth of private universities is creating new opportunities for study and research. There is thus a need to encourage partnerships between private and public institutions and collaboration locally and regionally (Njuguna and Itegi, 2013).

The Funding challenge
World-class RIs are expensive and often require significant funding, highly skilled scientists (human resource and capabilities), policy and regulation and enabling ecosystem. In Section 4.2 above, we discussed funding challenges related to agriculture and food systems, focusing on a sectoral perspective. In this section, we provide a broader context, briefly.

South Africa, Egypt and Nigeria contribute 65% of the entire research expenditure in Africa (DAAD and British Council, 2018). While some scholars argue that the research investment by Africans are generally minimal to make meaningful impact on research and development, others contend that Africa's research output does not correlate with the research funds the continent receives both from domestic and international sources. Bashour (2013) reveals that Africa receives the largest amount of research funds from the European Union (EU) compared to the amount of funds from the EU to Asia and Latin America. Nevertheless, Africa's contribution to global research output remains less than 2%. Wild (2018, p.1) also indicates that "African scientists are caught in a resource bind. High-tech science needs infrastructure, but that costs money – and scientific equipment is not high on African countries' spending agenda".

4.7 Summary of findings based on empirical data

This section provides discussion and analysis of the summary of findings based on the empirical data employing surveys, interviews and case studies conducted in this research. The discussions and analyses focus on stakeholders perspectives on the crosscutting issues in SSA's RI ecosystems. Figure 8 below presents an overview of respondents' perspectives on the key issues, all of which require attention. We unpack these themes further in the discussions that follow.

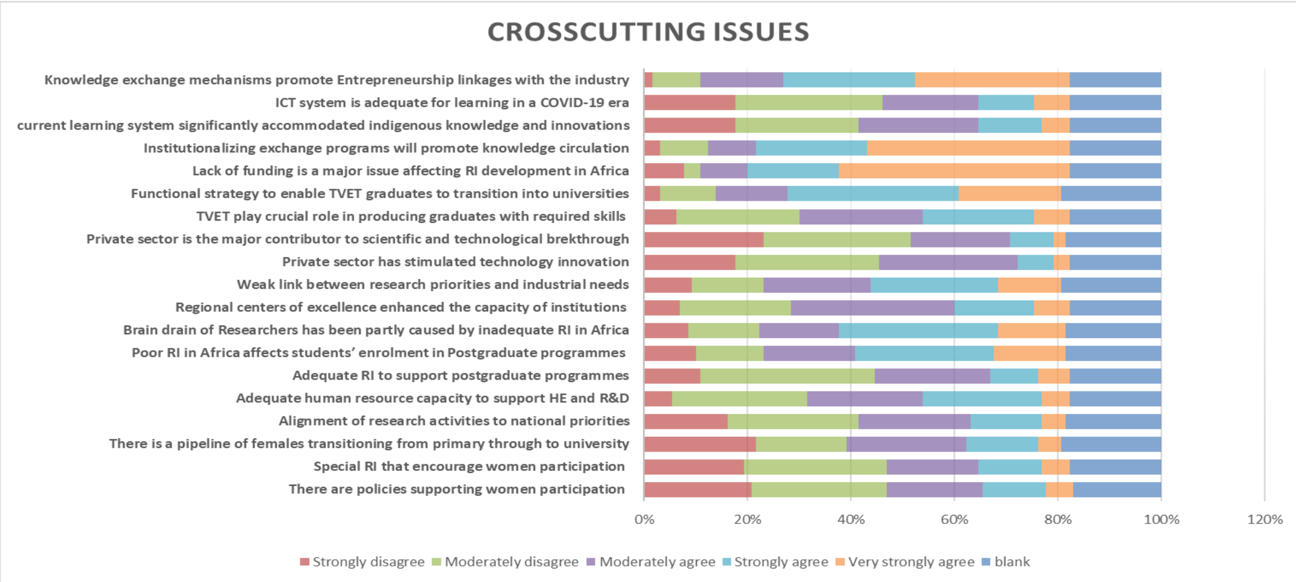


Figure 8: Crosscutting issues in RIs in HEIs and R&D in SSA

Private sector

The higher education sector in Africa has limited links with industries and the private sector[xxv]. University research and training has over the years laid less emphasis on the needs and demands of the industrial sector. This is typified by the weak linkage between private sector and university. This gap needs to be addressed to enable stronger relations between these two sectors which could increase the number of PhD students in Africa. The private sector, significantly, stimulates technology, innovation, entrepreneurship, and scientific research and development in SSA.

Gender and inclusivity

With respect to gender and inclusivity, respondents indicated that there is a pipeline of girls and women transitioning from primary through secondary to university training and R&D. And that policies are in place to support womens' participation in HEIs and R&D fields (Figure 8 above).

Addressing the funding challenge

Funding for RIs activities across Africa has been generally inadequate. Nevertheless, there are many steps that can be taken to address this challenge, as Figure 9 encapsulates. Respondents reported that interventions to help address the funding shortful could focus on patent buyouts, diaspora financing, and loan schemes, private sector contributions, impact investments and donations from charity organisations. Although international collaborative grants and development partners were reported to be 'moderately adequate' and 'very adequate' respectively, more should be done to strengthen these areas.

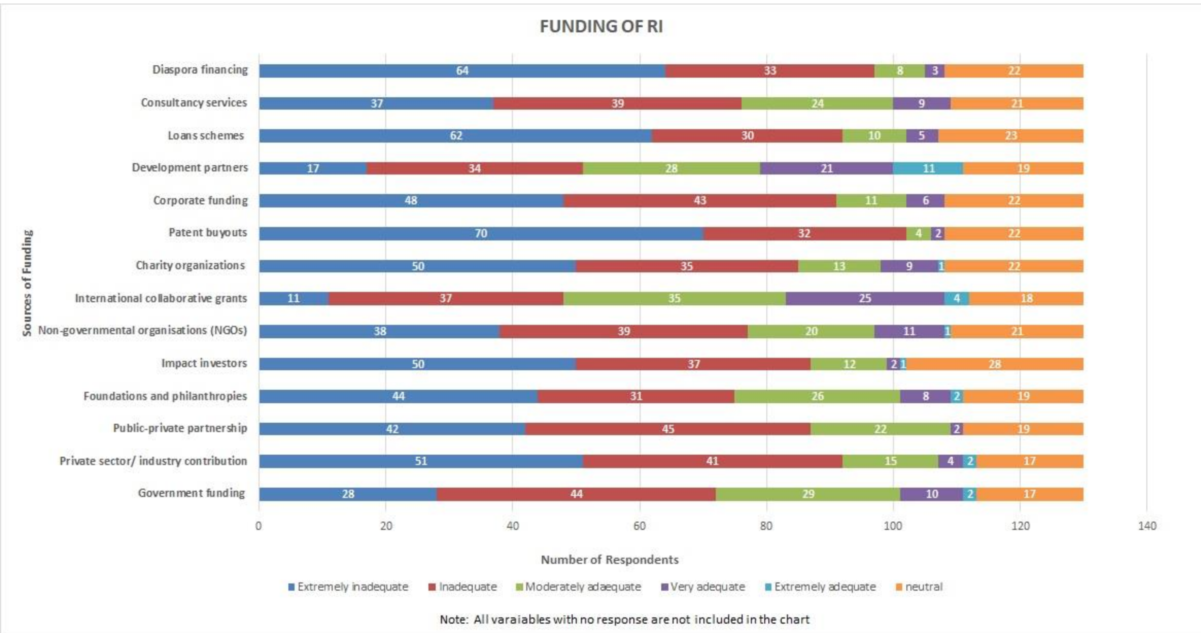


Figure 9: Funding of RIs in Africa

Allocating specific budgets for RIs development and maintenance in HEIs and R&Ds stands out as the most extremely effective strategy for strengthening RI development in Africa (Figure 9). A World Bank (2010) study reported that developing long-term strategies through capacity building for enhancing competence, updating knowledge of technology and virtual applications, fostering networking and collaboration between staff and students of HEIs within and outside Africa are equally highly recommended as bankable strategies that can strengthen RI in Africa (Figure 10).

In allocating specific budgets it is important to pay attention to the priority sectors, based on the empirical evidence gathered. The three top priority sectors for RI investment across the region according to respondents were: Agriculture and Food Systems (66%), Education (50%), and Health & Medicine (48%). Respondents ranked environment the lowest (19%) among all the sectors. Protection of the environment has never been a particularly high priority for African governments (Shinn, 2016). That could explain the low interest in RI investment in the environmental sector. The other low ranking sectors are Industry (27%), STEM (28%), and Energy (25%). The low ranking sectors are however important for Africa's industrialization ambitions and investments must be made in those sectors (Figure 11).

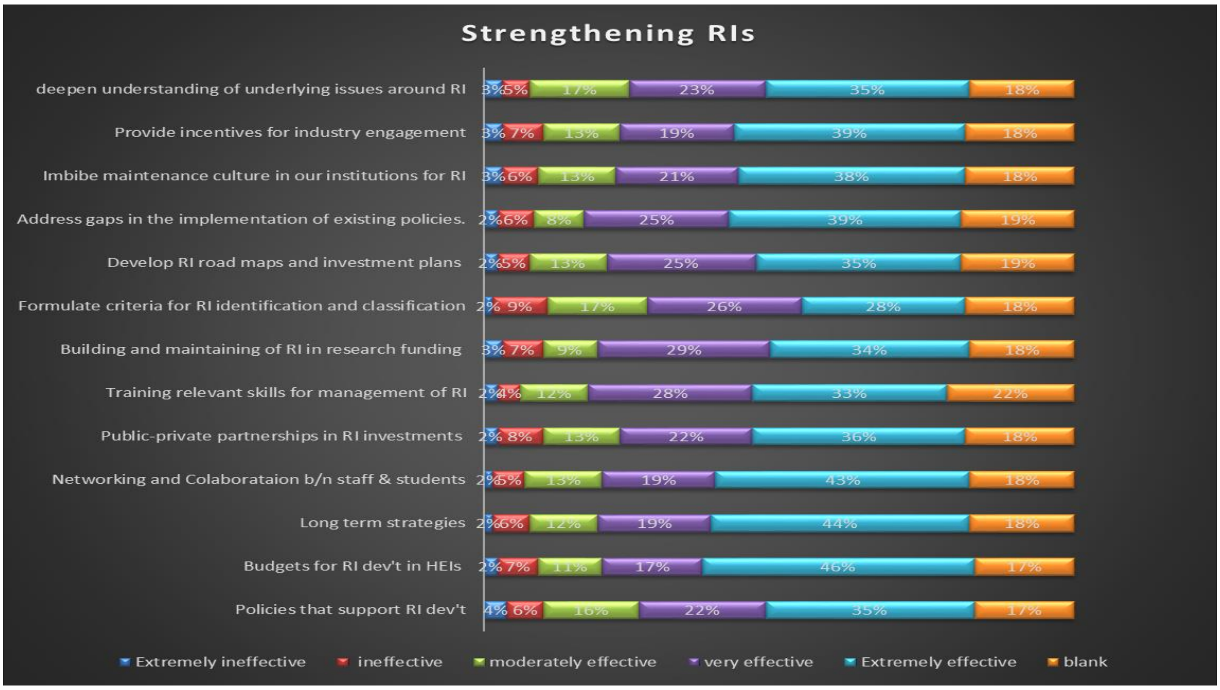


Figure 10: Strategies for strengthening RIs in Africa

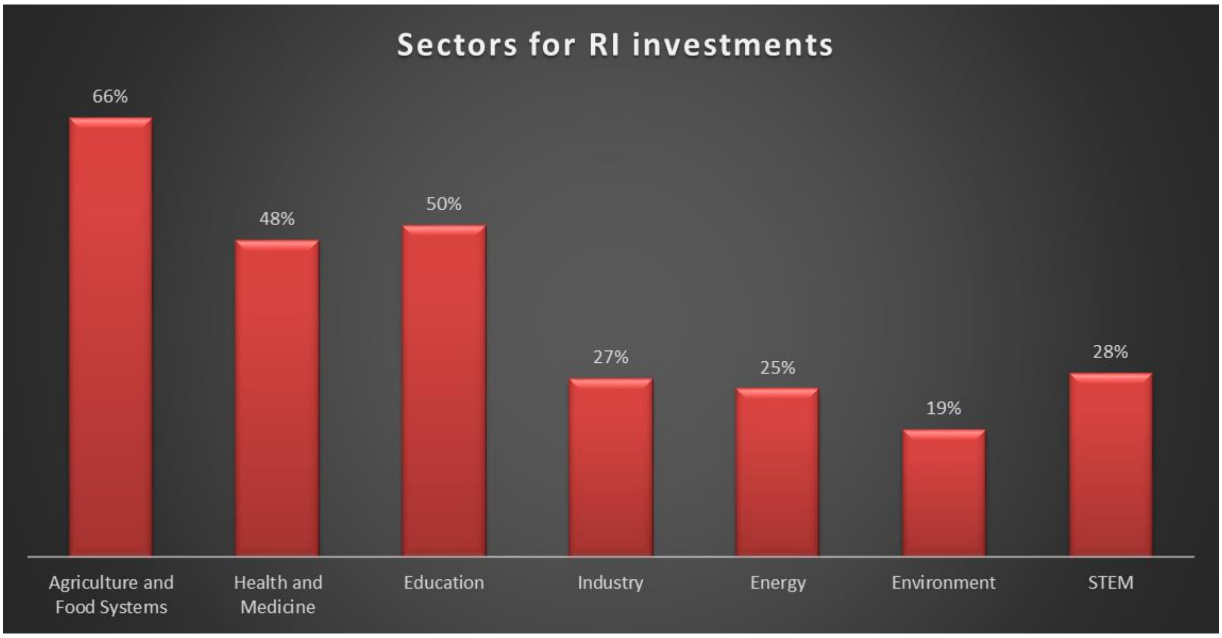


Figure 11: Priority sectors for RIs investment for transformative change in Africa

Learning and sharing experiences from countries like South Africa, where funding is centralised and inclusive, is an opportunity for sustaining RIs in SSA, for example, lessons from the Technology and Human Resources for Industry Programme (THRIP) approach in South Africa. THRIP funds applied research, design and engineering and technology development by bringing together researchers, academics, and industry players to cost-share grants across any number of projects.

Interview and focus group discussants noted that external financing was a major funding source for RIs and related research activities in SSA. This view aligns with the survey response. External support enables HEIs and R&Ds to engage in large cross-country institutional programmes. One such example is the Long-term Europe-Africa Programme for Food and Nutrition Security and Sustainable Agriculture (LEAP4FNSSA) and its related LEAP-Agri, which bring together 30 partner institutions in Africa and Europe with European Commission funding. Agencies such as IDRC, DANIDA, Sida, GIZ, and many UN agencies also support HEIs, R&D and innovation in SSA. In addition, the HEIs and R&D institutions generate funds internally to support research. The University of Zambia, for instance, provides its academic community with small grants for research in STEM and other disciplines. Public universities in Ghana, i.e., the University of Ghana, the University of Cape Coast, and Kwame Nkrumah University of Science and Technology (KNUST), provide research grants. However, the institutional grants are not substantial and need enhancement.

5. Strengthening RIs in Africa for Transformative Change: opportunities, governance, and sustainability

This section responds to Objective 3 of this research. As discussed in preceding sections, efforts to strengthen RIs in Africa, foster transformative change, harness opportunities from RIs, improve governance, and achieve sustainability transitions goals, must take into account and involve key stakeholders from SSA and beyond (including public and private sector actors). To achieve this, it is necessary to establish new links with stakeholders (where such links do not already exist) who have interests and abilities to mobilise knowledge or resources to improve access to and use of RIs.

As Figure 10 shows, efforts to strengthen RIs in Africa for transformative change must focus on specific areas of interventions. These research and policy intervention areas include: ensuring dedicated budgets for RIs development in HEIs, focus on longterm strategies, effective networking and collaboration between research/faculty staff and students, engagements with industry and the implementation of policies and regulations that foster progress in RIs.

Strengthening RIs in Africa can foster transformative change, improve opportunities for collaboration and research outputs, contribute to governance and improve the prospects of sustainability and resilience in ways that support long-term socioeconomic development. As discussed in preceding sections, RIs are fundamental to economic growth, sustainable development and transformative change. RI that enables high quality research, teaching and learning in HEIs is essential to strengthening science systems across the continent and achieving the continental Agenda 2063 and the SDGs. Excellence in research and science is vital, if Africa is going to realise her transformation aspirations. As COVID-19 has shown, world class research and strong science systems provided the basis for development of vaccines. Progress in these areas were made possible by the advanced levels of RIs – physical and virtual, human resources, funding, policies and regulations, and enabling ecosystem. Furthermore, the many opportunities that science and technology, entrepreneurship, innovation and the commercialisation of technologies, and digitalisation present to Africa may not be realised in the absence of excellent research and science systems, facilitated by robust infrastructures.

There are various ways the existing infrastructure foster research in HEIs, innovation and capability and competence building, research collaboration and technology transfer. Nevertheless, gaps in RIs across HEIs in Africa continue to hinder HEI research, innovation and capability/ competence building, research collaboration and technology transfer; exacerbate brain drain; and contribute to low involvement in STEM disciplines which do not match market demands. Beyond funding, other challenges contribute to limiting Africa's research output. Research priorities in Africa have generally focused on health sciences, social sciences, agriculture, education and engineering, however health research have dominated the research system in the past 10 years (Chataway et al, 2019). The majority of the research have focused on malaria, HIV/AIDS and maternal health and this to a large extent is influenced by the high degree of infectious diseases on the continent (Kasprowicz et al. 2020). This dominant research focus on health, in part, reflects the interests of funders such as Bill and Melinda Gates Foundation who's funding dedicated more into health research. In terms of research relevance, past studies have demonstrated a misalignment between research in HEIs and national agendas.

In spite of these challenges and gaps in RIs across Africa's HEIs, strengthening RIs in Africa can foster transformations that transcend sectors, systems and societies; enhance opportunities, contribute to governance and improve the prospects of sustainability and resilience. To achieve these gains, it is essential that gaps in physical and virtual RIs, especially data (see Box 7 below) and high-end computing facilities, poor digital skills among African academics and paywalls behind journal articles that restricts access to information are addressed, as a matter of urgency.

Box 7: The Role of Data and E-infrastructure in the Energy Sector

Two thirds of energy infrastructures report a 'significant e-infrastructure/data require mentor component'. E-infrastructure is seen as necessary by the sector to address the challenges of capturing data, undertaking complex modelling and the simulation of various subsectors/subsystems with the aim of ultimately being able to simulate the entire energy system. E-infrastructure is also needed for applied solutions to real sector issues, such as the real-time monitoring of remote facilities (e.g. wind farms) which is valuable for performance checks, early detection of faults and errors and ensuring the security of the system is intact. Three quarters of energy infrastructures consider that e-infrastructure and data will become more relevant over the next five to ten years. In the energy sector data are a particularly valuable resource that can be used to inform models, improve accuracy of forecasting and cost optimisation, inform policy interventions and help businesses to develop. These data can come in many forms, such as individual user data, weather data for prediction of peaks and troughs in electricity production, systems performance and control data needed for maintaining grid stability and market data for ensuring optimum efficiency for suppliers and consumers. It is important that researchers, businesses and aggregators have sufficient access to data to enable informed decisions. Hence, data are a valuable asset and are legally protected both as company property and the property of the individual customer.

Source (UKRI, nd, p.95)

5.1 Opportunities from RIs

There are many opportunities for transformation through contributions from RIs, with potentials for positive impacts at systems, national, regional and continental levels. Top sectors that represent some of the areas of opportunities where RIs can contribute to socioeconomic development, especially through virtual RIs, include manufacturing (pharmaceutical and electronics), agriculture, energy, services (health, and computing and communications), transportation (automative), utilities (energy), policies and regulations. A few examples to help contextualise opportunities for RIs contribution to socioeconomic activities and development include:

i. Enhancing collaboration, joint research projects and sharing of good practices.
ii. Boosting Africa's research outputs – publications, citations, patents and innovation.
iii. Improving linkages, interaction and interactive learning among researchers, but also between researchers and the wider NSI ecosystem actors and stakeholders.
iv. Knowledge sharing, peer learning or group work and networking that improves the prospects of idea generation and circulation that are essential to new project and product development, conceptualisation of (research, science and innovation projects and programmes) and funding applications.
v. Higher prospects for better utilisation of existing RIs – physical and virtual – in research, teaching, learning and other aspects including dissemination of research outputs and engagements. Improved dissemination of research outputs and engagements can potentially improve impacts.

To help realise these opportunities, specific challenges, particularly in relation to digital/virtual RIs will need to be addressed. These include the need to:

i. Address low broadband and internet speeds (Kasprowicz et al, 2020).
ii. Develop common standard and approaches to e-learning in Africa's HEIs.
iii. Ensure access to mobile data and connectivity (Faraj, 2020). For instance, some students are forced to access broadband services late at night or during off-peak hours. Others live in areas where connectivity is sporadic or inaccessible due to cost issues, while a third group do not have internet access at all.
iv. Improve energy (electricity) access and reliability. Often HEIs (staff and students) struggle to access consistent and reliable electricity to power their devices.
v. Address the low internet penetration rates. COVID-19 pandemic has been a stark reminder that Africa's internet penetration is still under 40%, well below the global average. COVID-19 has highlighted the need to move towards technology for blended learning. Universities are now expected to deploy management systems that house learning materials. This ensures that students are able to submit their assignments via digital platforms. This poses a challenge due to poor digital infrastructure.
vi. Address systemic infrastructure and funding issues that have hindered universities across SSA from effectively responding to the demand in STEM-related fields (Odera et al, 2020). The results of the survey on the impact of COVID 19 on researchers in Africa suggest a fractured system, exacerbated by a global pandemic. While 83% of respondents experienced disruption to their ongoing learning, 39% reported that they were enrolled in HEIs that offered e-learning options. 17% of West African respondents reported as being at HEIs with e-learning options, compared to 43% in East Africa and 41% in Southern Africa (Odera et al, 2020).
vii. Address the dearth of skilled e-learning practitioners, as well as lecturers that are skilled in the use of ICT. This is a major barrier to the successful integration of e-learning and ICT infrastructure in Africa's HEIs (see also Figures 2, 4 and 6).

5.2 Governance of RIs, collaboration and policies

Governance

Harnessing the opportunities outlined above requires effective governance frameworks and mechanisms. It is essential that in strengthening RI, careful attention is paid to the ecosystems in which HEIs operate. A key part of strengthening the ecosystem deals with improving governance – to help address weaknesses in coordination, collaboration, accountability and quality controls. Investments in RI must target ecosystem building in ways that enhance collaboration. An investment in RI ecosystem strengthening is an investment in generating evidence and not simply upgrading scientists' careers, which by itself is important.

There are strong financial, technical and human resources rationales that provide justifications for collaboration between universities in Africa. While good examples of cooperation exist, the arrangements for cooperation are frequently ad-hoc. Opportunities for more systematic cooperation arrangements needs to be supported by regional networks and intermediary organizations. If effectively harnessed, opportunities for collaboration among universities in Africa can help to build the region's collective capacity for higher education. Reasons for collaboration include engaging in joint research, peer learning on organizational and transformation processes, learning about degree programs, developing joint degree programs or courses, students and faculty exchanges, and capacity building.

One of the major challenges for STI to thrive in Africa is the condition of the ecosystem within which scientific and technological activities are carried out. Fundamentally, conditions must be supportive of these activities especially from the economic and commercial perspectives. For example, there must be venture capital to enable technology companies overcome market entry challenges and take roots. Where these companies are linked to the institutions with robust RIs, they contribute to the sustainability and growth of the STI institutions. There are only few venture capital enterprises on the continent with substantial resources to support start-ups to take root in the marketplace and most of them are not indigenous. A review of the top 10 major venture capitalists[xxvi] on the continent shows that their operations support business ventures in a wide range of areas including agriculture, telecommunications, e-business and industry. They operate in several countries such as South Africa, Ghana, Nigeria, Kenya and Mauritius. However, their investments in ventures are yet to directly buttress the operations of some of the excellent RIs on the continent and therefore this must be addressed.

Linked to ecosystem enhancement is the operation of technology and innovation hubs and centres (Dosso et al, 2021; Martins et al, 2021). Currently these hubs and centres are opening up and operating in several African countries. What remains to be seen is the strong linkages to the knowledge institutions – the universities and research institutions – with excellent RIs. Knowledge institutions, such as universities, generally have established their own technology transfer centres. However, where private sector technology hubs are operating and connect with the knowledge institutions, they provide a more entrepreneurial approach to commercialisation of locally developed technologies and this must be encouraged.

Although RIs have been gaining popularity in Africa, the maturity in the governance if RIs is still low. Relatedly, RIs and 4IR adoption face challenges in technical, content, human resources, and financial readiness (Oketch, 2013). This finding aligns with key informant responses which stated that RIs governance, readiness of HEIs and R&Ds to embrace 4IR, and policy implementation are still weak in Africa. The failure of RIs to help reduce brain drain in Africa has also exposed weaknesses in the state of RIs governance in Africa. With the current weaknesses in RIs governance across Africa, some of the best talents and brains will probably continue to migrate to Western countries with better RIs and supporting policies. The empirical evidence point to monitoring and evaluation as the next important factor hindering the governance of RIs in Africa.

Collaboration

Finances and the COVID-19 pandemic were quoted most during the interviews. However, working in collaboration with jointly managed facilities also came up frequently. Interviews and focus group discussants emphasised the importance of collaboration with individuals or joint funding at various levels, both internally and externally, for purposes of research, innovation, development projects, and the procurement of a variety of RIs. Internally, there are cross-disciplinary collaborative R&D activities in the STEM disciplines and among cognate departments, schools, colleges and research centres. Externally, collaborations occur between governments (or public institutions) and universities, private institutions and universities, and between universities in a country and other universities within and outside the country. There are also various partnerships between units at the institutional and national levels and external or foreign funders. For example, the National Science and Technology Council (NSTC) facilitates bilateral and multilateral research activities among South Africa, Zambia and Mozambique with support from United Kingdom's Department for International Development (DFID), Canada's International Development Research Centre (IDRC), South Africa's National Research Foundation (NRF), and the Swedish International Development Cooperation Agency (SIDA). Also, the National Research Foundation of South Africa and the Strategic Research Fund of Zambia jointly funded 19 projects in 2015.

The evidence from interviews and focus group discussions reveal that the following factors necessitate/encourage collaboration in SSA:

i. The need to acquire expensive or complex equipment. Such equipment may come through projects with sharing requirements in order to avoid duplication of equipment and research effort.
ii. The creation of professional bodies also promotes collaborative work. An example is the Engineering Council of South Africa (ECSA).
iii. Disparity and the need to bridge the gap also necessitate collaboration. Some policies mandate more privileged groups to partner with underserved communities or groups for research and the sharing of RI.
iv. Common interests in research enables collaboration within and across countries, and within or across sub-regions. For example, many HEIs and R&D in Africa engage in

climate change adaptation. Examples of collaborative projects include the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL).

In addition, it was argued that Private Public Partnerships (PPPs) can increase access to RIs when promoted through policy. The Zambia national science and technology council (NSTC) uses this to promote R&D policies to ensure and sustain partnerships. The NSTC encourages research/project proposals to reflect PPP agenda, and such proposals stand a greater chance of consideration and approval for funding. PPP is also quite robust in Nigeria. For instance, the University of Lagos had a convocation and received about 200 million Nigerian Naira from the private sector to expand its ICT unit. This is a case in point where collaborations and partnerships contributes in opportunities for financial progress.

Furthermore, research collaboration between civil society groups and the community was put forward as an area that should be considered. In some parts of SSA, the concept and practice of 'adoption villages' has made traction. This is where a university 'adopts' a village as a case study or for an experiment to develop tangible solutions. Furthermore, there are increasingly more innovation hubs in STEM and allied disciplines that collaborate with international development partners such as the United Nations Development Programme (UNDP) to support new innovation hubs and that are willing to partner with academia for research and development.

At an institutional level, senior researchers, professors and other key players in the R&D landscape are part of the HR components of RI. Therefore, RI collaboration opportunities also entail mentoring young and upcoming researchers especially in the STEM disciplines.

Policy awareness

Related to governance and collaboration are policies and regulations that support RIs and the governance of RIs. Table 3 outlines relevant policies across selected SSA countries, indicating the presence of policies and regulatory frameworks governing the development of RIs in HE and R&D in Africa. Nevertheless, as Figure 13 shows, only 38% of the respondents were aware of existing RIs policies in their countries while a majority of the respondents, 47%, had no idea of existing policies in their countries (Figure 12).

Awareness goes beyond policies and extends to RIs themselves in terms of knowledge of RIs that exist in specific HEIs. One way to solve the awareness gap, the problem of duplication of equipment and the issue of needs-equipment mismatch is to map RI in the country. The Ministry of Science and Technology of Zambia mapped its research capacity to understand what was available. The information was disseminated to leverage opportunities through networking and prioritising bridging the gaps with limited funding. Publicity of available research equipment (and how to operate/use them) can enhance access and optimal utilisation and also help to avoid duplication. For example, at the University of Johannesburg, each department must declare/ publish their available equipment and other resources for research on their website. Awareness creation is critical.

Table 3: RI policies across SSA

S/N	Country	Policy and year of enactment
1	Nigeria	• National Policy on Education, 2020 • Tertiary Education Trust Fund, 2011
2	Kenya	• Science and Technology Act of 2013
3	Ghana	• Science Technology and Innovation Policy, 2017
4	Namibia	• National Intellectual Property Policy, 2019
5	Botswana	• National Policy on Research, Science, Technology and Innovation, 2011
6	Uganda	• Science Technology and Innovation Policy, 2009
7	South Africa	• Research Outputs Policy, 2015 • South Africa Research Infrastructure Roadmap (SARIR) 2016
8	Zambia	• The National Policy on Climate Change, 2016
9	Namibia	• National Space Science and Technology Policy, 2021
10	Tanzania	• The National Research and Development Policy, 2010
11	Ethiopia	• National Science Policy and Strategy, 1993

Source: authors

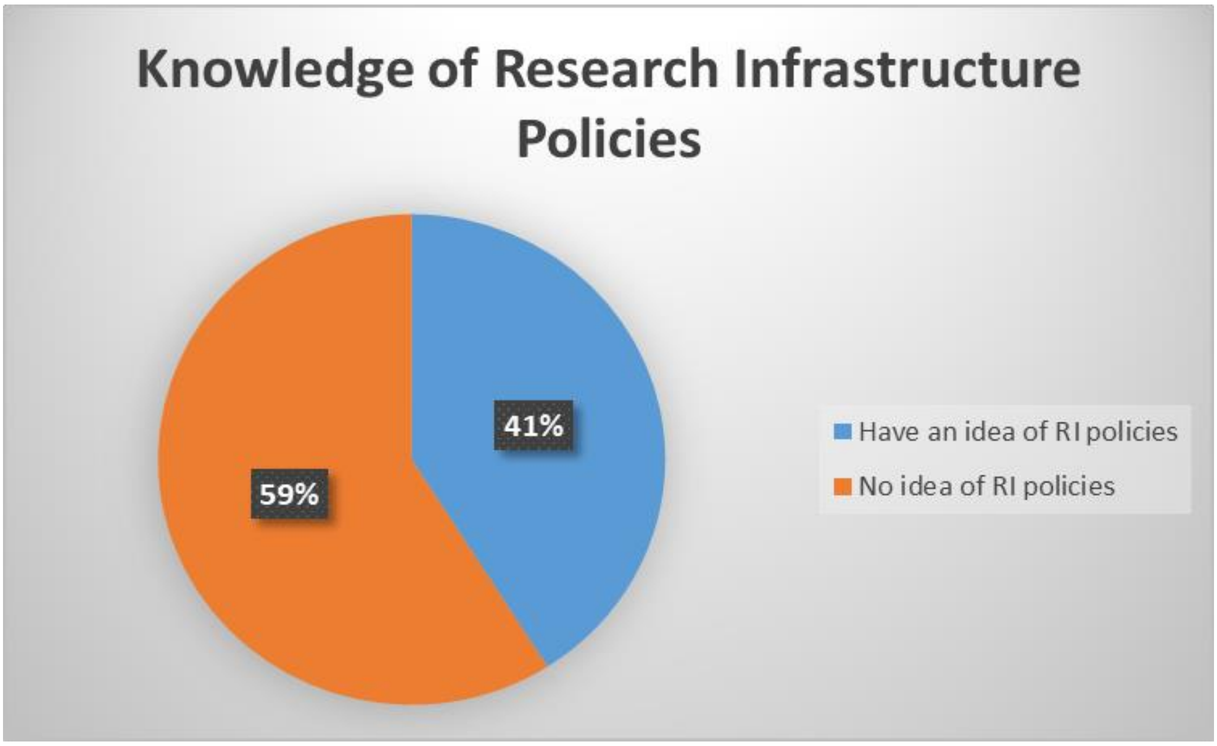


Figure 12: Respondents knowledge of RIs policies in SSA

From the interviews and focus group discussions, research policies are considered guidelines or standards that spell out procedures or give clear directions for research, thereby contributing to HEIs ability to increase research results. Robust research policies protect research and provide insurance for researchers. From the expert interviews and the discussions, teams deduced that not many HEIs and R&D organisations in SSA have clear working policies. SSA countries' best practices are mainly from South Africa, with an R&D Roadmap, R&D taxing policy, technology transfer policy, and RI funding policies.

South Africa's National Research Foundation (NRF) encourages partnerships between HEIs and companies to conduct research and solve problems. When companies commit financing to support R&D through NRF, a member of the company's board is allowed to sit on the NRF board. A position on the NRF is lucrative as it allows the member to communicate industry challenges that require research and informs the NRF calls to HEIs and R&D organisations.

Most countries in SSA have policies and strategies for STI and R&D frameworks and national research agendas, many of which are outdated or under review. For example, Nigeria's National Policy for Technology and Innovation dates back to 1989 and has undergone several revisions. Ghana's National Science, Technology, and Innovation Policy (2017-2020) is more recent but ready for review. Tanzania's R&D Policy is from 1996, and the STI Policy has been in draft for some years. At the institutional level, most HEIs and R&D have the requisite policies and strategies which address RI. However, the gap is in support and alignment at a national level. Possession of policies and strategies that are not implemented is a challenge in SSA. Governments need to develop and implement plans. One reason for the inaction of policies on STI and R&D was the change in government, administration, or leadership in some countries. In the absence of institutionalisation, stability and sustainability are a challenge.

The next section unpacks sustainability in further detail.

5.3 Sustainability and Resilience

RIs are long-term investments; hence sustainability of RIs is of utmost importance. To ensure sustainability, stable financial support and a long-term investment plans are required. African countries with thriving RI rely on funds from national governments and international funders (Vicente-Crespo et al, 2020). However, funds from international funders accounting a larger share of R&D and STI in Africa is such that it raises issues of sustainability with implication for long-term resilience of the research and science systems. For example, with Nigeria's GDP totalling USD$520 Billion, 1% of GDP, as advanced for R&D in multiple regional and continental declarations, would mean USD$5.2 Billion. This would mean USD$2.46 Billion for Egypt and USD$1.23 Billion for Angola (AUC, 2014, p.43). These are substantial financial resources which could massively contribute to improving RIs on the continent. It is essential that the AU and various African countries implements the recommendation to commit 1% of their GDP to R&D.

Evidence from interviewees and focus group discussants noted various avenues for improving sustainability, thereby, contributing to strengthening RIs in SSA. These areas of focus include

Joint management facilities: There are few opportunities for joint acquisition, management, expansion and sharing of RI. However, the economies of proximity encourage collaboration.

Coupled with funding problems, the proximity of HEIs and other R&D units encourages collaboration to purchase or share equipment. This is especially relevant to those scarce and not-easy-to maintain equipment. In South Africa, for instance, there is provincial proximity sharing of infrastructure. Joint management of facilities creates opportunities for sharing ideas and leveraging network opportunities. Beyond facilities, sharing of human capital through mentoring was noted by interview respondents and focus group discussants as an important area for consideration. SSA is yet to attain a critical mass of expertise and thus the movement and sharing of R&D and Innovation expertise are encouraged. Institutional relations for collaboration can enhance the establishment of facilities, open up avenues for funding, strengthen competencies for research and support sustainability pathways.

Promoting sustainability through improvements in the maintenance of RIs can help in multiple ways:

i. Building resilience: There should be long-term plans at various levels (national, institutional, international) as in Ghana's 50-year plan) with vertical policies that will withstand political changes. In addition, RI development must be linked to the overall development goals of nations to ensure continuity in the research enterprise and the relevance of projects to national development;
ii. Centralising resources: When specialised laboratories and other major RI components are centralised for sharing, they are easier to maintain. Centralised management will partly help address the challenge of scarce funds to procure and maintain expensive equipment. Furthermore, centralisation also resolves the problem of duplication, underutilisation and redundancy;
iii. Internationalisation: SSA countries need to link the national agenda with global, regional, and sub-regional R&D goals to sustain RI projects as well as policies;
iv. Capacity building: Internally, there should be intentional capacity building to boost the HR component of RI to maximise the utilisation of RI in general;
v. Role of ethics: Respecting ethics and standard practices in research and RI management is another way to promote sustainability; and
vi. Data protection and safe sharing: Data security, safe sharing, and preservation through reliable means can enhance the sustainability of RI.

6. Conclusion

The second Strategic Objective (SO) of the African Union's Continental Education Strategy for Africa 2016 - 2025 (CESA 16-25)[xxvii] emphasise the need to "Build, rehabilitate, preserve education infrastructure and develop policies that ensure a permanent, healthy and conducive learning environment in all sub-sectors and for all, so as to expand access to quality education" (AUC, 2016, p.8). CESA acknowledges that although policies and strategies exist in some cases, the implementation in terms of infrastructure, "has been generally very slow" (AUC, 2016, p.14).

This project on *Mapping RI to Enhance the Resilience of Science Systems in SSA* unpacked the current RI landscape, both physical and virtual, in Africa. The findings offer fresh insights and ideas on ways that improvements in RIs in HEIs can enhance academic knowledge generation, strengthen Africa's research and science systems, and contribute to socioeconomic development and long-term transformation.

6.1 Concluding remarks

RIs in African HEIs must the conceptualised, designed, operated and managed as a strategic capability, with a long-term view and in a co-creation involving HEIs, industry, government (Triple Helix) and other actors of the ecosystem. Taking this approach, can help improve governance, enable collaboration, foster innovation, improve operation, reduce duplication and enhance regulatory compliance and policymaking. Collaborative governance and joint management of RIs will help ensure equity in access, reduce maginalisation, and achieve the goal of leaving no one behind.

Governments across Africa need to develop long-term strategic roadmaps for RIs development, alongside strengthening R&D and STI ecosystems. Currently, the majority of international funds on research exclude provisions for RIs development as they focus, predominantly, on the implementation of research projects. This dependence on development partners must change as it has implications on the development, sustainability, resilience and strengthening of science systems in Africa. Addressing the many gaps identified in our findings require interventions on many fronts and active collaborations.

Collaboration in this sense must go beyond HEIs but also involve invitation to the private sector to share experiences and expectations with HEIs and R&D. In addition, there is need to develop and promote virtual infrastructure (e.g., virtual libraries and digital technologies) as this can help enhance access to resources for STEM research and encourage collaboration among universities and research centres. The promotion of intra-Africa collaboration is vital. Aside from the advantage of joint fiscal strength to develop RIs, it will encourage sharing, promoting unity, research, and development in SSA. Intra-Africa collaborations can help address current gaps and provide relevant solutions for the region. In addition, intra-Africa collaboration can help promote capacity building to attain a critical mass. The gap in interaction between Anglophone and Francophone Africa would also diminish if this was promoted actively. Collaboration was considered beneficial and a key source for resourcing RIs and promoting research and development. The existing collaborations must be strengthened and enhanced within countries and across countries.

Research and knowledge sharing at institutional, national, and global levels is the bedrock of innovations. This calls for strategies to provide free and better access to knowledge. Open access must be promoted in respect of published literature and bibliographic databases for the benefit of African scientific institutions where funding for accessing these knowledge resources is limited or even lacking.

CESA 16-25 points the increased recognition, at high policy levels, of the importance of RI in achieving Africa's socioeconomic development objectives. This improved awareness and recognition is essential to strengthening and prioritising the development of RIs across the continent. Nevertheless, it is far from clear how best to formulate, implement, evaluate and govern policies, strategies and frameworks on RI at regional and continental levels to ensure mutually reinforcing and complementary benefits for countries in Africa.

Strong RIs are vital for Africa's excellence in research to addressing Agenda 2063 and global challenges encapsulated in the SDGs. Therefore, the development, management and governance of RI in Africa must be at the core of the national, sub-regional and continental efforts to advance Africa, economically and socially.

The disruption in research, teaching, and learning in HEIs by the COVID-19 pandemic have brought to the fore the importance of quality RI in HE. The disruption also exposed the gaps that need to be addressed swiftly to position Africa at a place where it will fully take advantage of the scientific and technological revolution sweeping the world.

Our findings bring us to several recommendations that can enhance the resilience of science systems in Sub-Saharan Africa through robust RI as noted below.

6.2 Recommendations

I—Recommendations to HEIs in Africa

The AAU, with support from relevant partners, such as the IDRC, should engage with HEIs within the AAU's network[4] to:

i. Conduct a comprehensive mapping of RIs in HEIs and declare/publish the available equipment and other resources for research on the relevant locations, such as, websites.

[4] Currently, this is about 450 HEIs and a high number of African Centres of Excellence (ACEs) across Africa. See: https://www.aau.org/subs/membership/?_ga=2.82186645.2030130918.1666181114-1862018326.1657031599 for HEIs and https://ace.aau.org/ for ACEs

ii. Formulate, develop, implement, and maintain RI roadmaps and plans to support regular mapping[xxviii].
iii. Establish adequate institutional arrangements to ensure effective governance, implementation, and M&E of RI roadmaps and plans in HEIs.
iv. Create internal funding sources and mechanisms for RIs development and maintenance within individual HEIs but also across HEIs at regional and national levels.
v. Develop a long-term strategy for enhancing competence and knowledge of academic and other relevant staff in educational technologies and virtual applications.
vi. Address the "ivory tower" mentality in academia that often hinders effective collaboration with industry and other actors and stakeholders of RI and innovation ecosystems.
vii. Seek out and exploit avenues for co-development, co-funding, co-sharing, co-management and joint governance of RIs with industry (private sector).
viii. Develop strategies for active engagements and collaborations with industry in R&D that results in mutual benefits including joint patents, innovations (in terms of commercialisable products).
ix. Initiate, under the auspices of relevant university governing bodies[xxix], inter-institutional RIs that are shared and jointly utilised among neighbouring HEIs. This is vital in cases of high-end and very expensive RIs.
x. On gender, improve research and data collection on women's progression in science to help deepen our understanding of the factors, including politics and power dynamics, that influence the governance of RIs and the implications on the research and academic careers of female scientists. To achieve this, develop, support and strengthen mechanisms to consider females in the STEM disciplines.
xi. On inclusivity, improve research and data collection on the roles that RIs play in the progression of young and early career researchers in science, in addition to the career of professional and support staff. Programmes should allocate a percentage of funds for persons living with disabilities/ physically challenged. ICT facilities should be inclusive and accommodate all individual users' needs.

II—Recommendations to governments – especially at national levels but could also include governments at the levels of RECs and the AUC

The AAU, using its position as "The Voice of Higher Education in Africa", should work with relevant partners, such as the IDRC, the World Bank and European Commission, to convene high-level meetings with governments. Such high-level engagements will help to:

i. Develop roadmaps and investment plans to guide progress in RIs development at national, regional and continental levels. This is because inadequate funding remains the main challenge for RIs development in SSA. The heavy reliance on development partners to fill the funding and investments gaps must be urgently addressed.
ii. Formulate a set of criteria to guide the mapping (identification and classification) of RIs in Africa.

iii. Increase education, research, and R&D funding, starting with the agreed 1% GERD and 4% investment in education.
iv. Foster networking and collaboration among a) faculty and students in HEIs in Africa, b) among HEIs and c) between HEIs and private sector; thereby promoting innovation.
v. Enhance capacity strengthening to support RIs development and management.
vi. Work with HEI and innovation ecosystems actors and stakeholders to close the gap in virtual infrastructure – starting with data, broadband and internet connectivity costs, reliability and access.
vii. Improve stakeholders' knowledge of the political and economic factors that influence the sharing of RI funding, human resources development, policies and regulations, and related factors.
viii. Address implementation gaps in current policies that relate to HEIs and innovation; in doing so, emphasise the centrality of RIs. Where applicable, revise / update current policies and deepen understanding of underlying issues that hinder RIs in HEIs across Africa.
ix. Address governance – including coordination, collaboration and accountability - challenges – alongside structural barriers that disincentivise interactions, co-creation and co-learning among HEIs.
x. Explore avenues to improve contributions of the African Diaspora in RIs development, management and governance.
xi. Examine the (dis)incentives for private sector actors to engage in RIs development, management and governance. For example, the use of policy instruments such as R&D tax credits, or avenues to enhance co-purchasing, co-location, co-hosting, and sharing facilities between industry and HEIs.
xii. Improve interactions and cooperation with the private sector, promote technology hubs and venture capitalists. In doing this, strengthen linkages among R&D, NSI/STI ecosystem actors and stakeholders.
xiii. Enhance capacity building among African researchers especially through regional and North-South partnerships and enhance Public-Private Partnerships in more purposeful manner.

III—Recommendations to development partners / external funders

The IDRC, should lead in this area, working with other development partners who are active in the African HE landscape, such as SIDA, the World Bank, the United Nations, Carnegie Corporation of New York, and the European Commission, to help ensure that research, funding and project proposals and implementation strategies:

i. Include components for building or improving relevant RIs in research funding calls and innovation programmes and projects. Funding in this regard reflects the priority on RIs in research projects and helps to highlight the importance of RIs to national governments and ecosystem actors.

ii. Increase efforts to address contextual challenges and the roles that RIs can play in this regard to fostering international collaboration in research projects which enhance capacity and competence in African HEIs.
iii. Foster engagements with government, private sector and other key stakeholders as this is crucial to enhancing the building and sustainability of research projects in RIs in Africa.
iv. Encourage joint applications between HEIs and industry actors in funding research projects in Africa,
v. Include RIs, as dedicated thematic areas, in research project calls and funding.
vi. Support HEIs in setting up dedicated state-of-the-art research centres in each African country. This will improve access, mitigate brain drain, and boost skills retention.

IV—Recommendations to private sector at national levels in Africa

Private sector actors are either unaware of the RIs challenges or lack the capacity or interest to contribute to the transformative change that is required in this area. To this end, the AAU, working with key selected development partners and government agencies, should engage with private sector actors in ways that help improve their (private sector actors's) prospects to:

i. Adopt an open-minded approach to collaboration with HEIs in R&D that aligns with national contexts and development goals.
ii. Invest in RIs that contribute to innovation in individual industry's and organisation's lines of business. For example, the case of Guinness, Ghana, which uses local sorghum in the development of drinks and beverages.
iii. Volunteer to open up research and innovation facilities for capacity building to HEIs in areas such as training and internships while at the same time benefiting from the knowledge transfer that emanates from HEIs to industry.
iv. Establish strategies for active engagements and collabotations in research with HEIs.
v. Foster greater appreciation of the role of HEIs in research and innovation that underpins production and industrial growth; and the importance of RIs in the processes involved. With this in mind, work with HEIs in expediting actions on RI development, co-funding, colocation, co-hosting and sharing of facilities.

6.3 Further study

The areas of further research summarised below are based, predominantly, on the discussions and analyses provided in Sections 4 and 5, which highlighted gaps in gender and inclusivity (Section 4.6.1), human resource (Section 4.6.2), funding, private sector and the role of industry (Section 4.6.3), policies and regulations (Section 4.5), and governance (Section 5.2). The final area for further study, which relates to the need for renewed focus on university-industry linkages, is covered in (Section 4.6.3) but also in the ajority of the report.

Gender and inclusivity: Further research are needed on gender and inclusivity, especially on female scientists in Africa. Such research can help to deepen our knowledge on issues that relate to i) the dynamics of RI and gender in STI and STEM; ii) the role of politics, power dynamics and governance of RI in relation to women scientists and researchers; and iii) barriers to effective collection and analyses of data on women researchers, their outputs, innovations.

Human Resource – PhD enrolments and completion: Overall, there has been a considerable increase in the number of PhD enrolment in Africa; however, there is also a sharp decline of master's degree conversions into PhD studies. The extent to which these trends are influenced by RI requires further exploration. Discussions and interventions on PhD programmes are key to research capacity. For example, to what extent do the state of RIs influence student's decision to enrol in PhD programmes? What are the implications on national research agenda?

Funding: It is important to unpack further the role of funding, which remains a major issue affecting RI in Africa. Research in this area can help to provide deeper insights on funding for research and RI (which has remained persistently low in African countries), the political economy factors (including ideas, narratives, governance, structures, policies and regulations that influence and shape investments in RI) and the implications on the broader research and innovation ecosystems.

Private sector: Effective university-industry is core to innovation. Research, led by academia but involves private sector actors is needed to help improve our understanding of why private sector investments in RI – in addition to R&D and STI – has remained weak. This will provide finding on empirical evidence and recommendations to help improve university-industry linkages and engagement.

Governance, colocation and sharing: The majority of RI in Africa's HEIs are still located within individual institutions. Research is essential to help deepen our knowledge of the ways in which the governance of RIs can be improved to foster greater levels of colocation, co-funding, management and sharing of RIs among HEI and between HEIs and industry actors.

Policies and regulations: Further research will help to generate empirical evidence that explains the inabilities in the translation of research-supported discourses into effective practices, policies and regulations that relate to RIs in Africa.

University-industry linkage: University-Industry linkages are vital to innovation and economic growth. On this backdrop, it is important to carry out a deeper study on the factors that inhibit active, sustained and engaged collaboration between academia and industry in Africa.

References

A4AI (Alliance for Affordable Internet), 2020 report, https://a4ai.org/affordability-report/report/2020/

Abugre, 2017

African Union Commission (AUC) (2014). Science, Technology and Innovation Strategy for Africa 2024, AUC

AUC (2015a). Agenda 2063, The Africa We Want, Popular Version, AUC

AUC (2015b). Agenda 2063, First Ten-year Implementation Plan 2014–2023, AUC

AUC (2016). Continental Education Strategy for Africa (CESA) CESA 2016-2025. Addis Ababa, AUC, https://au.int/sites/default/files/documents/29958-doc-cesa_-_english-v9.pdf

Ali W. & Elbadawy A., (2021) Research output of the top 10 African countries : An analytical study, COLLNET Journal of Scientometrics and Information Management, 15:1, 9-25, DOI: 10.1080/09737766.2021.1934181

Akudolu, L. R and Adeyemo, S. K. (2018), A Study on Research and PhD Capacities in Sub-Saharan Africa: Ethiopia Report. (Online). (Viewed January 2021). Available from https://www2.daad.de/medien/der-daad/analysen-studien/research_and_phd_capacities_in_sub-saharan_africa_-_nigeria_report.pdf

Asare R. and Essegbey, G. 2016. Funding of Agricultural Research and Development in Ghana: The Case of Council for Scientific and Industrial Research (CSIR), Technology and Investment, 7, 40-50, 10.4236/TI.2016.72006

ASTI (2017) IFPRI/ ASTI Database https://www.asti.cgiar.org/benchmarking/ssa

Awuni, S. and Essegbey, G.O. (2014) Developing An Enabling Scientific Equipment Policy In Africa: The Ghana Country Study, A Report Submitted to IFS and AAS, CSIR-STEPRI, Accra.

Bashir, S. (2020). Connecting Africa's Universities to Affordable High-Speed Broadband Internet: What Will it Take?, World Bank, http://documents1.worldbank.org/curated/en/337151607685646967/pdf/Connecting-Africa-s-Universities-to-Affordable-High-Speed-Broadband-Internet-What-Will-it-Take.pdf

Beintema, N. and Stads, G., (2014). Taking Stock of National Agricultural R&D Capacity in Africa South of the Sahara ASTI Synthesis, https://reliefweb.int/sites/reliefweb.int/files/resources/astiafricasynthesis.pdf

Blom, A., George Lan and Mariam Adil (2016) *Sub-Saharan African Science, Technology, Engineering, and Mathematics Research – A Decade of Development*, The World Bank, Washington D.C.

BCSD (Broadband Commission for Sustainable Development), (2019). *Connecting Africa Through Broadband*. Retrieved from https://www.broadbandcommission.org/Documents/working-groups/DigitalMoonshotforAfrica_Report.pdf

Brown, K.A., Lada Timotijević, Marjolein Geurts, Johanne L Arentoft, Rosalie AM Dhonukshe-Rutten, Léopold Fezeu, Paul Finglas, Martine Laville, Giuditta Perozzi, Marga Ocké, Krijn Poppe, Nadia Slimani, Harriette M Snoek, Inge Tetens, Pieter van't Veer, Cécile Vors, Karin L Zimmermann (2017) Concepts and procedures for mapping food and health research infrastructure: New insights from the EuroDISH project, *Trends in Food Science & Technology* 63, DOI: 10.1016/j.tifs.2017.03.006 https://www.researchgate.net/publication/314465231_Title_Concepts_and_procedures_for_mapping_food_and_health_research_infrastructure_New_insights_from_the_EuroDISH_project[accessed Feb 06 2021].

Campbell, S., and Jenkins, M. (2006). *Transforming the University: Recommendations of the Task Force on Research Infrastructure*. Retrieved from University of Minnesota website: http://conservancy.umn.edu/handle/11299/5673

Cele, M.B., Luescher, T.M., Fadiji, A.W., 2020. Innovation policy at the intersection: Global debates and local experiences. HSRC Press.

Chataway, J., Dobson, C., Daniels, C., Byrne, R., Hanlin, R., Tigabu, A., 2019. Science granting councils in Sub-Saharan Africa: Trends and tensions. Science and Public Policy 46, 620–631. https://doi.org/10.1093/scipol/scz007

Chataway, J., Hanlin, R., Kaplinsky, R., 2014. Inclusive innovation: an architecture for policy development. Innovation and Development 4, 33–54.

Chataway, Joanna, & Daniels, Chux. (2020). The Republic of Science meets the Republics of Somewhere: Embedding scientific excellence in sub-Saharan Africa, 39-58. http://doi.org/10.5281/zenodo.3607326. In Kraemer-Mbula, E., Tijssen, R., Wallace M. L. and McLean, R (eds) Transforming Research Excellence: New Ideas from the Global South. Cape Town: African Minds

Cozzens, S., Sutz, J., 2014. Innovation in informal settings: reflections and proposals for a research agenda. Innovation and Development 4, 5–31. https://doi.org/10.1080/2157930X.2013.876803

DAAD and British Council (2018). A Study on Research and PhD Capacities in Sub-Saharan Africa. (Online). Viewed January 2021. Available from https://www.britishcouncil.org/sites/default/files/h233_07_synthesis_report_final_web.pdf

Daniels, C., 2017. Science, Technology, and Innovation in Africa: Conceptualizations, Relevance, and Policy Directions. What Do Science, Technology, and Innovation Mean from Africa 169.

Daniels, C., Byrne, R., Hanlin, R., Pointel, S. and Numi, A. (2020b). Updating the case studies of the political economy of science granting councils in Sub-Saharan Africa, research project technical report, available at: https://idl-bnc-idrc.dspacedirect.org/handle/10625/59314

Daniels, C., Dosso, M., and Amadi-Echendu J. (eds.) (2021). Entrepreneurship, Technology Commercialisation, and Innovation Policy in Africa, Springer Nature, Cham., https://doi.org/10.1007/978-3-030-58240-1

Daniels, C., J. Schot, J. Chataway, M. Ramirez, E. Steinmueller and L. Kanger (2020a), Transformative Innovation Policy: Insights from Colombia, Finland, Norway, South Africa, and Sweden. In Innovation policy at the intersection Global debates and local experiences, Cele MBG, TM Luescher and AW Fadiji, HSRC

Daniels, C.U., Ustyuzhantseva, O., Yao, W., 2017. Innovation for inclusive development, public policy support and triple helix: perspectives from BRICS. African Journal of

Science, Technology, Innovation and Development 9, 513–527. https://doi.org/10.1080/20421338.2017.1327923

Delvaux, P. A. G, Riesgo, L. and Paloma, S. G., (2020). Sustainable agricultural practices and their adoption in Sub-Saharan Africa. (online). (Viewed January 2021). Available from: https://op.europa.eu/en/publication-detail/-/publication/29428254-249a-11eb-9d7e-01aa75ed71a1/language-en

Department of Science and Technology (2017) South African Science, Technology and Innovation Indicators 2017, Department of Science and Technology, Pretoria. Available at http://www.naci.org.za/wp-content/uploads/2018/07/South_African_Science_Technology_And_Innovation_Indicators_Report_2017.pdf

DST (Department of Science and Technology) (2016). South African Research Infrastructure Roadmap (SARIR), https://www.dst.gov.za/images/Attachments/Department_of_Science_and_Technology_SARIR_2016.pdf

DST (Department of Science and Technology), (2002) *South Africa's National Research and Development Strategy*, Department of Science and Technology, Pretoria. Available at https://www.gov.za/sites/default/files/gcis_document/201409/rdstrat0.pdf

Dosso M., Braoulé Méïté F., Ametepe G., Gbogou C., Guiella G., Oulaï D. (2021) New Entrepreneurial Narratives in Urban West Africa: Case Studies of Five Innovation Hubs and Communities. In: Daniels C., Dosso M., Amadi-Echendu J. (eds) Entrepreneurship, Technology Commercialisation, and Innovation Policy in Africa. Springer, Cham. https://doi.org/10.1007/978-3-030-58240-1_8

Essegbey, G., Nouhou Diaby & Almamy Konte (2015) "West Africa", in *UNESCO Science Report Towards 2030*, UNESCO, Paris. pp. 470-497.

Essegbey, G., Almamy Konte, Natewinde Sawadogo and William Siyanbola (2020 forthcoming) "West Africa", in *UNESCO Science Report 2020*, UNESCO, Paris.

Essegbey, G. O. and Asare, R., (2014). Assessment of agricultural research capacities in Ghana: the case of council for scientific and industrial research (CSIR). Available from: https://www.asti.cgiar.org/pdf/coraf/Ghana-Report.pdf

ESFRI (European Strategy Forum on Research Infrastructures) (2018). Roadmap 2018. Strategy Report on Research Infrastructures, http://roadmap2018.esfri.eu/media/1060/esfri-roadmap-2018.pdf, accessed 10 February, 2021

ESFRI (2011). Strategy Report on Research Infrastructure Roadmap 2010, European Strategy Forum on Research Infrastructures (ESFRI) https://ec.europa.eu/research/infrastructures/pdf/esfri-strategy_report_and_roadmap.pdf accessed Feb 06 2021.

Etzkowitz, H., 1996. The Triple Helix: Academic–Industry–Government Relations. Annals of the New York Academy of Sciences 787, 67–86. https://doi.org/10.1111/j.1749-6632.1996.tb44849.x

Faraj, G., (2020). The Impact of COVID 19 on universities in Africa. . (online). (Viewed January 2021). Available from:https://www.accord.org.za/analysis/the-impact-of-covid-19-on-universities-in-africa/

Foster, C., Heeks, R., 2014. Nurturing user–producer interaction: inclusive innovation flows in a low-income mobile phone market. Innovation and Development 4, 221–237. https://doi.org/10.1080/2157930X.2014.921353

Freeman, C., 1987. Technology, policy, and economic performance lessons from Japan.

Gwenzi, W., and Rzymski, P. (2020). When silence goes viral, Africa sneezes! A perspective on Africa's subdued research response to COVID-19 and a call for local scientific evidence. *Environmental Research*, 110637. https://doi.org/10.1016/j.envres.2020.110637

Hafkin, N. J., (2016). National Assessments on Gender and Science, Technology and Innovation A review of four country assessments from East Africa: Ethiopia, Kenya, Rwanda and Uganda, https://owsd.net/sites/default/files/NH4EastAfricaGEKS.pdf

Ibrahim, H., Kamour, A. M., Harhara, T., Gaba, W. H., and Nair, S. C. (2020). Covid-19 pandemic research opportunity: Is the Middle East & North Africa (MENA) missing out? *Contemporary Clinical Trials*, *96*, 106106. https://doi.org/10.1016/j.cct.2020.106106

IEA (International Renewable Energy Agency), United Nations Statistics Division, The World Bank, and World Health Organization. (2019). Tracking SDG 7: The Energy Progress Report 2019. *The World Bank*, 176. Retrieved from www.worldbank.org

IFS (2012) Addressing Equipment Challenges in Development-related Scientific Research in Africa, IFS Briefing Document 1/2012, available at http://www.ifs.se/IFS/Documents/Publications/Briefing%20Documents/IFS%20Briefing%20Document%201-2012.pdf

IFS (2014) An Enabling Scientific Equipment Policy In Africa, Available at http://www.ifs.se/ifs-news/an-enabling-scientific-equipment-policy-in-africa.html

Iliopulos, I. and Boyd, C. (2019) Preventing a Dirty Bomb: Case Studies and Lessons Learned, Nuclear Threat Initiative, Washington D.C.

Kilama, W. L. (2009). The 10/90 gap in sub-Saharan Africa: Resolving inequities in health research. *Acta Tropica*, *112*(SUPPL. 1), S8–S15. https://doi.org/10.1016/j.actatropica.2009.08.015

Kosprowicz et al., (2020). African-led health research and capacity building- is it working? *BMC Public Health.* 20, 1104. doi.org/10.1186/s12889-020-08875-3

Kraemer-Mbula, E., Tijssen, R., Wallace M. L. and McLean, R (eds) (2020). Transforming Research Excellence: New Ideas from the Global South, African Minds

Lee, H., Park, Y., & Choi, H., (2009). Comparative evaluation of performance of national research and development programmes with heterogeneous objectives: A DEA approach. *European Journal of Operational Research.* 196, 847–855.

Lundvall, B.-Å., 1992. National systems of innovation : towards a theory of innovation and interactive learning.

Lundvall, B.-Å., 2010. National Systems of Innovation Toward a Theory of Innovation and Interactive Learning, Anthem Other Canon Economics. Anthem Press, London.

Lynam, J., Beintema, N. and Annor–Frempong, I., (2012). Agricultural R&D: Investing in Africa's future analyzing trends, challenges, and opportunities reflections on the conference. (online). (Viewed January 2021). Available from: https://www.asti.cgiar.org/pdf/ASTI-FARA-Conference-Synthesis.pdf

Makoni, M. (2018). Survey highlights concerns over research infrastructure, https://www.universityworldnews.com/post.php?story=20180413101931390

Martins R.M., Park E., Hain D.S., Jurowetzki R. (2021) Mapping Entrepreneurial Ecosystem for Technology Start-ups in Developing Economies: An Empirical Analysis of Twitter Networks Between Start-ups and Support Organizations of Nairobi's Digital Economy. In: Daniels C., Dosso M., Amadi-Echendu J. (eds) Entrepreneurship, Technology Commercialisation, and Innovation Policy in Africa. Springer, Cham. https://doi.org/10.1007/978-3-030-58240-1_4

Mbaye, R., Gebeyehu, R., Hossmann, S., Mbarga, N., Bih-Neh, E., Eteki, L., … Boum, Y. (2019). Who is telling the story? A systematic review of authorship for infectious disease research conducted in Africa, 1980-2016. *BMJ Global Health*, *4*(5), 1855. https://doi.org/10.1136/bmjgh-2019-001855

Mokwunye, U. (2010). Regional review of Africa's agricultural research and development. (online). (Viewed January 2021). Available from:http://www.fao.org/fileadmin/user_upload/rome2007/docs/Regional_Review_of_Africa_Agricultural_Research_and_Development.pdf

Muthumbi, J., (2015). Africa's women in science. (online). (Viewed January 2021). Available from:. https://www.who.int/tdr/research/gender/Women_overview_piece.pdf

Nelson, R.R., 1993. National Innovation Systems: A Comparative Analysis. Social Science Research Network, Rochester, NY.

Njuguna, F. and Itegi, F., (2013). Research in institutions of higher education in Africa: challenges and prospects. European Scientific Journal. 1, 1857 – 7881

Ouedraogo, B. (2017). Model of Information and Communication Technology (ICT) Acceptance and Use for Teaching Staff in Sub-Saharan Africa Public Higher Education Institutions. Higher Education Studies, 7, 101. https://doi.org/10.5539/hes.v7n2p101

PAERIP (2019) *Final Report Summary - PAERIP (Promoting African – European Research Infrastructure Partnerships)* available at https://cordis.europa.eu/project/id/262493/reporting accessed 6th Feb. 2021

Ramoutar-Prieschl, R. and Hachigonta, S., (2020). Management of Research Infrastructures: A South African Funding Perspective. Switzerland: Springer. doi.org/10.1007/978-3-030-37281-1

Ranga, M. and H. Etzkowitz (2013). 'Triple Helix Systems: An Analytical Framework for Innovation Policy and Practice in the Knowledge Society", Industry and Higher Education 27 (4): 237-262.

Sam-Agudu, N. A., Paintsil, E., Aliyu, M. H., Kwara, A., Ogunsola, F., Afrane, Y. A., … Ezeanolue, E. E. (2016). Building Sustainable Local Capacity for Global Health Research in West Africa. *Annals of Global Health*, *82*(6), 1010–1025. https://doi.org/10.1016/j.aogh.2016.10.011

Sawyerr, A., (2004). African Universities and the Challenge of Research Capacity Development. *Journal of Higher Education in Africa / Revue De L'enseignement Supérieur En Afrique*, *2*(1), 213-242.

Schot, J., Steinmueller, W.E., 2018. Three frames for innovation policy: R&D, systems of

innovation and transformative change. Research Policy 47, 1554–1567. https://doi.org/10.1016/j.respol.2018.08.011
Shende, M., & Reddy, B. M. (2020). Integration of ICT in Higher Education Institutions: Scope and Challenges.
Shinn, David H. (2016) "The Environmental Imact of China's Investment in Africa," *Cornell International Law Journal*: Vol. 49 : No. 1 , Article 2. Available at: https://scholarship.law.cornell.edu/cilj/vol49/iss1/2
Simpkin, V., Namubiru-Mwaura, E. and Mossialos, E., (2019). Investing in health R&D: where we are, what limits us, and how to make progress in Africa. *BMJ Glob Health*. 4(2). doi: 10.1136/bmjgh-2018-001047
Southern African Development Community (SADC) Gender Policy, (2007). (online). (Viewed January 2021). Available from: https://www.sadc.int/files/8414/0558/5105/SADC_GENDER_POLICY_-_ENGLISH.pdf
STEPRI (2014). Report of Scientific Equipment Policy Study of Ghana. Accra: Science and Technology Policy Research Institute. (online). (Viewed January 2021). Available from: https://www.csir.org.gh/images/CSIR-STEPRI_Reports/STEPRI%202014%20Annual%20Report%202.pdf
Task Force Rural Africa (2018). An Africa-Europe agenda for rural transformation, https://ec.europa.eu/info/sites/info/files/food-farming-fisheries/farming/documents/report-tfra_mar2019_en.pdf, accessed, January 2021
Tiedeu, B. (2020). Moves are afoot in Africa to keep more women in science careers. (online). (Viewed January 2021). Available from: https://theconversation.com/moves-are-afoot-in-africa-to-keep-more-women-in-science-careers-133641
Tijssen, R. and Mbula, E. K, (2018). Research excellence in Africa: Policies, perceptions, and performance. *Science and Public Policy*. 45 (3), 392 403. https://doi.org/10.1093/scipol/scx074
Toom, K., and Miller, P. F. (2018). Research Infrastructure. In *Research Management: Europe and Beyond* (pp. 205–212). https://doi.org/10.1016/B978-0-12-805059-0.00009-2
Ukpokodu, O.N., (2020). Diaspora Migrations: Brain Drain or Symbioses. In: Abidogun J., Falola T. (eds) The Palgrave Handbook of African Education and Indigenous Knowledge. Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-030-38277-3_37
UKRI (nd). The UK's research and innovation infrastructure: Landscape Analysis, https://www.ukri.org/wp-content/uploads/2020/10/UKRI-201020-LandscapeAnalysis-FINAL.pdf, accessed 10 February, 2021
UNESCO Institute for Statistics (2015). Researchers per million inhabitants (FTE), (online). (Viewed January 2021). Available from http://data.un.org/Data.aspx?d=UNESCO&f=series%3AST_SCRMIFT
UNESCO (2019). Regional overview: Sub-Saharan Africa: UNESCO Science Report, Towards 2030. (online). (Viewed January 2021). Available from: https://en.unesco.org/unesco_science_report/africa

Vicente-Crespo, M., Agunbiade, O., Eyers, J., Thorogood, M., and Fonn, S. (2020). Institutionalizing research capacity strengthening in LMICs: A systematic review and meta-synthesis. *AAS Open Research*, *3*, 43. https://doi.org/10.12688/aasopenres.13116.2

Wood, J. V., León, G., Von Gruenewaldt, G. and Botha, A. P., (2013). A South African Research Infrastructure Roadmap (online). (Viewed January 2021). Available from: https://www.dst.gov.za/images/pdfs/SARIR%20Report%20Ver%202.pdf

World Bank (2010). Financing higher education in Africa. Washington, D. C.: The World Bank. Available from: https://elibrary.worldbank.org/doi/10.1596/978-0-8213-8334-6

World Bank (2019). Strengthening Higher Agricultural Education in Africa. (online). (Viewed January 2021). Available from: http://documents1.worldbank.org/curated/en/979781600349826090/text/Executive-Summary.txt

Wild, S., (2018). Africa's scientific infrastructure gap, (Online). (Viewed January 2021) Available from https://www.africaportal.org/features/africas-scientific-infrastructure-gap/

Annexes

Annex 1: Methodology

In this section we provide the detailed methodology and steps undertaken for each of the work packages (WP).

Desk Research [WP1]

In this component of the project (desk research), we review the relevant information available, including documents and historic data, before the in-depth study takes place. The purpose of the desk research is to help build a good understanding of the research infrastructures situation in particular sectors and settings across Africa, examine evidence on the evolution of RIs, and uncover data gaps. More specifically, the desk research helped to uncover long-term socio-economic trends; and provided key information on the various ramifications of the subject matter.

In this respect, this literature review critically examined secondary data on RI using selected keywords and criteria that help to unpack issues around funding, human resource (HR), policies and regulations, ecosystem dynamics and political economy factors that shape and influence research infrastructure in SSA. This activity focuses on three fields of science: (a) agriculture and food systems, (b) health and medicine, (c) STEM, and a fourth area of importance, (d) policy and regulations as they influence RIs. HR and Gender are dealt with as cross-cutting areas of investigation. These fields of science were selected for reasons that include i) their importance in relation to socioeconomic development and transformation of the African continent, ii) reliance on research and RI, and iii) the link to innovation. The choice of these fields is consistent with prior similar studies that have attempted to analyse or map RIs at a national, regional or continental level[xxx].

Materials reviewed include academic papers and journals, books, grey literature, reports, and online sources, policies and regulations. The research activities and ensuing analyses in this work package cover all parts of Africa, subject to availability of empirical evidence and relevant information in the literature. In this report, we focus on research (and innovation) infrastructures in Africa's HEIs, the majority of which are provided by government funding. These research infrastructures are predominantly accessible to users from, and within, the individual HEIs and within academic circles. The research infrastructures are in general, less accessible to the other research and innovation ecosystem actors and stakeholders, such as industry, and the wider society.

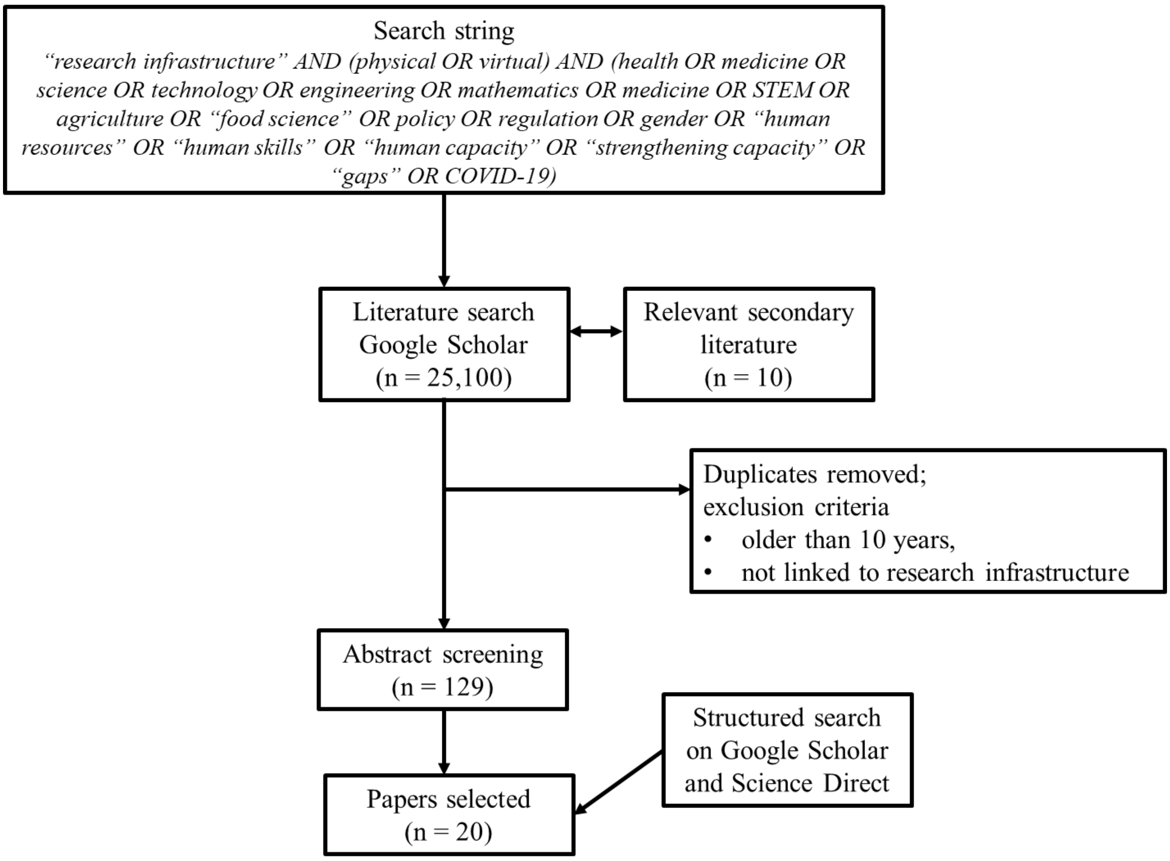
In line with the objectives above, this desk research was guided by three research questions:

1. In what ways do gaps in RI hinder the growth and resilience of robust research systems in Africa?

2. What are the existing and emerging RIs that Africa and opportunities for access to emerging research technologies on a global scale that HEIs in Africa can benefit from?
3. Who are the key stakeholders from Africa and beyond (including public and private sector actors) with interest and ability to mobilize knowledge or resources to improve access to and use of RI? And how best to establish new links to these actors?

The literature search utilised controlled vocabulary and free-text terms combining components (inclusion criteria) such as "research infrastructure", “higher education”, “physical” and “virtual”. The search strings were filtered with terms that include the fields described above, for example, COVID-19, “health”, medicine”, “food science”, “stem”, “gender” and “human resources”. The online sources and databases search utilised include Web of Science, Google scholar, Mendeley, Science Direct, National and international websites. Figure 1 below presents a schema of the literature search.

Figure 1 (Annex 1): Literature Search Schema



Source: authors

The activities in this WP contributes to answering the three research objectives, which encapsulates the research questions.

Online Survey via Questionnaire Administration [WP2]

The second activity (WP2) was the design and delivery of online survey via questionnaire. The aim was to help capture the overarching factors that respondents consider vital to identifying the gaps and opportunities and scope for strengthening research infrastructure in SSA. This activity will drew from the literature review and relevant secondary data such as those recently gathered by the AAU and other partners. The survey questions / instrument was tested to ensure that there were no ambiguities in the questions, which helped to reduce potentials for bias and improve robustness. Subsequently, the questionnaire was shared online for completion. This enabled the archiving of information and facilitated data analysis. Broadly, there will be two broad levels of activities.

Characteristics of demographics

This survey was conducted across 28 African countries and had 130 respondents. The majority of the respondents, 95% came from Anglophone countries while only 5% came from francophone countries (Figure Annex 1.1). The countries that had the highest number of respondents were Ghana (21%), Nigeria (19%), and Kenya (15%) while some of the countries that had the least number of respondents were Rwanda, Senegal, Malawi, Sudan, and Lesotho which had (1%) each (Figure Annex 1.1).

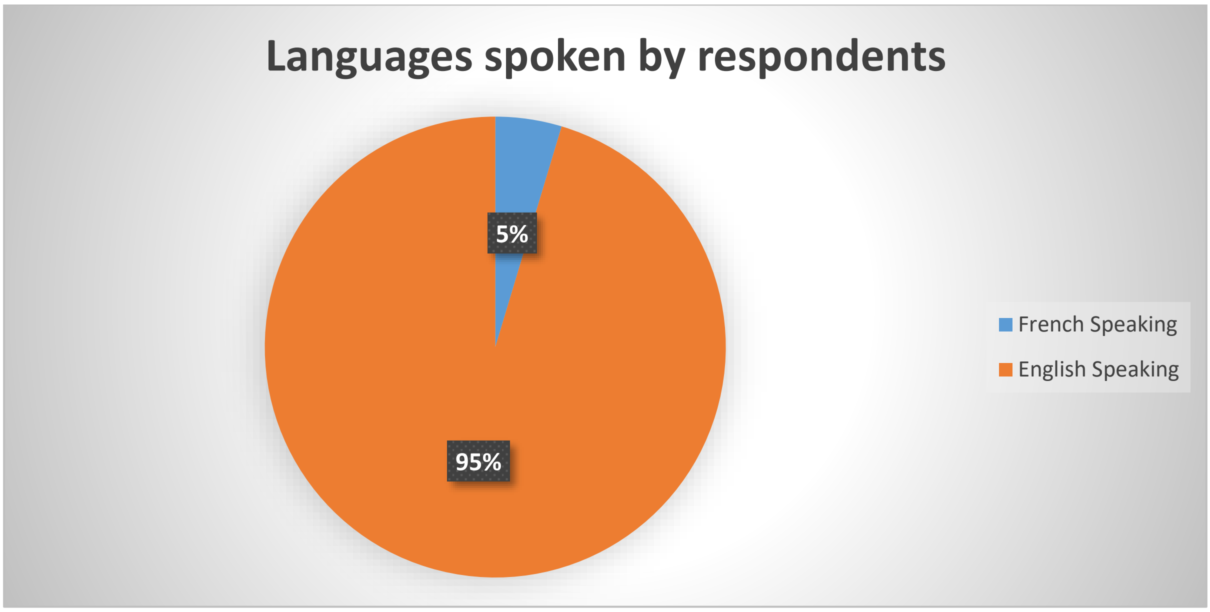


Figure 2 (Annex 1): Languages spoken by respondents in the 28 sub-Saharan African countries

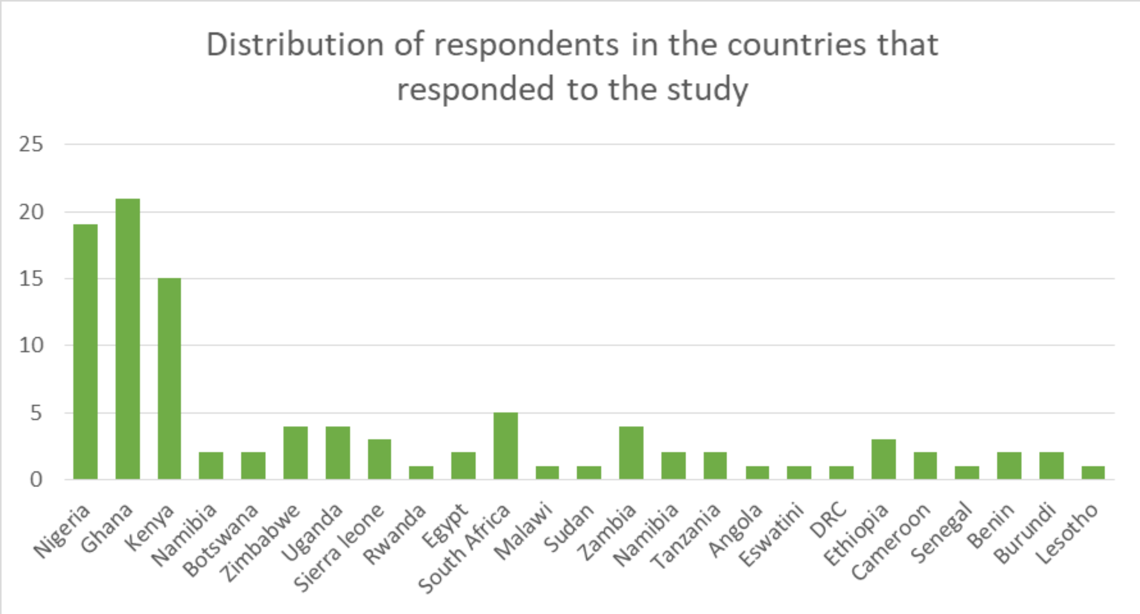


Figure 3 (Annex 1): Countries that responded to the study in Africa

The largest pool of respondents was drawn from the Higher Education Institutions (54%) and the lowest turnout (3%) was drawn from Industry organizations as illustrated in figure 3 below.

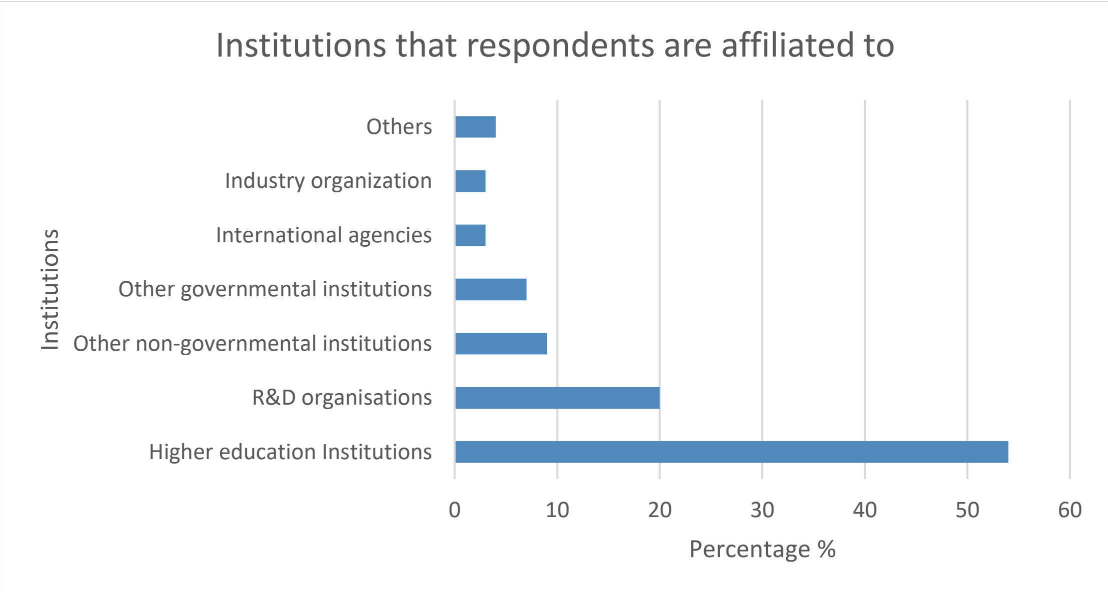


Figure 4 (Annex 1): Graph showing institutions that respondents of the study are affiliated to

Expert Interviews with Selected Actors [WP3]

Building on WP 1 and WP 2, the WP 3 team conducted ten expert interviews to gain deeper insights into the secondary data from the literature reviewed and the survey responses (See Annexes 4). The expert interviews focused on answering the"why" to explain the data from WP1 and WP2. Notably, the expert interviews did not repeat all questions from the survey but picked out those that warranted additional information to explain"why" these were packaged into seven key areas (See Annex 6).

The WP 3 team selected experts to interview from the AAU database, the ATPS network and the team's professional networks. Criteria for selecting experts were based on availability and consent, Gender, Geographic location, language, and area of expertise. Unlike WP 1 and WP 2, the scoping for experts went broader than Science Technology, Engineering Mathematics (STEM) to draw on an understanding of the influences of non-STEM elements[5].

The interviews were conducted virtually from November 2021 to January 2022, as COVID-19 Pandemic travel restrictions made it challenging to have face to face discussions. The team used an interview guide with seven questions (See Annex 6) on the key areas with an option to ask to follow on questions. The interview time was one and a half hours to limit virtual fatigue. The WP 3 team recorded the meetings on MS Teams after receiving consent from the interviewed expert. The recordings were shared with the interviewed experts following the meeting.

Focus group discussions [WP4]

The WP 4 team sought consensus on the "why" from WP 3 in smaller groups. Individual experts' opinions (WP 3) add narrative to the literature review (WP1) and the online survey (WP2) but may not necessarily articulate an agreed understanding.

The WP 4 team organised two online discussions in March and April 2022 that included participants from different Research fields to engage with one another and debate around three main topics. The aim was to validate the concept of RI as defined under WP 1, draw out solutions to address gender biases, and leverage opportunities for collaboration as part of the solution to gaps identified in WP 2 and reiterated in WP 3. Unfortunately, language and scheduling limited participation and only one of the discussions met the criteria for a Focus Group Discussion[6] with eight participants.

The other discussion only had two participants; however, their responses are included in the results due to the richness and clarity of the issues presented. WP 4 team recruited participants through a collective invitation via the AAU mailing list to about 2000 researchers in higher educational institutions and research centres across Africa. Ten researchers agreed to participate in the FGDs. The participants were mainly from the natural sciences, engineering and social science disciplines. Table 1 (Annex 1) shows the demographics of the participants of the Focus Group Discussion

[5] The interviews included experts who commercialise or incubate STEM practitioners.
[6] Effective focus group discussions generally have eight to ten participants, and it is recommended that there be four to five for online groups.

Table 1 (Annex 1): Demographics of the participants included in the discussions

S/No	Organisation	Field of Research	Country	Gender
1	University of Fez	Medicine and Pharmacy	Morocco	Male
2	University of Ibadan	Pharmacy	Nigeria	Female
3	Universite Felix Houphouet Boigny,	Tropical Geography	Ivory Coast	Male
4	Universite Felix Houphouet Boigny	Human and Economic Geography,	Ivory Coast	Male
5	Kwame Nkrumah University of Science and Technology	Environmental Science	Ghana	Male
6	University of Cape Coast	Geodetic Engineering	Ghana	Male
7	University of Cape Coast	Geography and regional planning	Ghana	Male
8	University of Ibadan	Gender Studies	Nigeria	Female
9	Council for Scientific and Industrial Research (CSIR)	Sociology	Ghana	Female
10	University of Cape Coast	Epidemiology and Biostatistics	Ghana	Male

The WP 4 team briefed participants on the purpose of the overall study and sought their consent before conducting the session. The discussions were in the English Language and supported by a professional translator to offer French translation for participants from the Francophone Countries. The duration of each discussion was about one hour and 30 minutes. The WP 4 team observed ethical research principles of anonymity and safety with the FGD participants. The discussions were recorded on MS Teams and shared with the participants after the meeting. In addition, the research team took notes to complement the recorded discussions.

Data Analysis for WPs 3 and 4

The meeting recordings from WP 3 were transcribed, coded, and analysed with MAXDQA 20 for thematic content[7]. The thematic content of the interview transcripts formed the basis for identifying common themes, specifically the sub-codes in the text presented for analysis. The codes were drawn from the interview questions.

[7] Thematic Content Analysis (TCA) is a descriptive presentation of qualitative data. Qualitative data may take the form of interview transcripts collected from research participants or other identified texts that reflect experientially on the topic of study.

The codes, which are the themes/ categories per question and subcodes identified in the coding process, are included in Table 2 (Annex 1): below:

Table 2 (Annex 1): Codes and Subcodes from the transcripts

Code/ Category	Sub-code (terms commonly mentioned in relation to code)
Importance/ Role of RI	Meaning of research infrastructure
	Contribution at the regional level
	Contribution at the institution level
	Contribution at the national level
Policies	National policy or guidelines
	Institutional policy or guidelines
Accessibility	Enablers
	HEI and R&D
	Marginalised groups
	Market promotion
Challenge	Acquisition
	Advancement of technology
	Cost and competence
	Development and retention of human capital
	Maintenance of RI
	Underutilisation of available Infrastructure
Collaboration	Level of engagement
Opportunities	Awareness
	Financial support
	Improve infrastructure
	Increase agricultural productivity
	Joint management facility
	Pandemic
Sustainability	Build resilience
	External support
	Internal support
	Effect of COVID-19
	Role of governance and management

The data was analysed to generate the following:

i) Codeine – This displays code occurrence or coverage using colour.

ii) Code Theory Model – This model evaluates how many transcripts contain two codes. The model displays a code icon at the centre of the map and sub-codes or memos in the outer circle. The numbers in brackets connote frequencies.

The responses from the FGD participants of WP 4 were transcribed and used to complement the analytical results from WP 3 as the data set was too small.

Case studies on research infrastructure in selected HEIs and ACEs [WP5]

Building on the data gathered in the prior work packages above, case studies focusing on selected HEIs, countries and fields of study in SSA will be conducted to help contextualise the study, and improve the robustness of the research and the findings. Five Case Studies from STEM centres of excellence (CoEs) will be commissioned on research infrastructures. The STEM CoEs will be selected from those centres that took part in the First Phase of the ACE Project. This criterion is used because those STEM centres of excellence in the current phase of the project (2019-2023) that participated in the first phase (2014-2020) performed very well since they were competitively selected based on internationally benchmarked standards. We will further select some of the CoEs which did not do well for investigation as this approach will enrich the data and we will not run the risk of producing only positive results. Indeed the weak centres will reveal more gaps; while the strong centres will provide us with more data on the available opportunities. Also, the selection of the CoE will take into account the disciplinary fields and geographic diversity of Africa.

Dissemination and stakeholder events [WP6]

The findings of the research infrastructure mapping study will be presented at a key stakeholders workshop at the end of the project in Ghana. Participants will include government functionaries responsible for education, science and technology; vice chancellors and presidents of African universities; leaders of thought; development partners; researchers; academics, and postgraduate students. The workshop will, *inter alia*, discuss the report and its recommendations, as well as get buy-in from the HEI community, policy makers and development partners on some of the recommendations as practices or a roadmap for research infrastructures in SSA.

The importance of quality training and scientific research, as well as their linkages with socioeconomic development, is addressed during the AAU Statutory Meetings and its various capacity strengthening initiatives. The AAU Statutory Meetings, such as the Conference of Rectors, Vice Chancellors and Presidents of African Universities (COREVIP) held every two years and General Conference held every four years, are geared towards examining themes of major concern to African Higher Education. These events provide opportunities for exchanging ideas, information and experiences among member institutions. They further serve as key platforms for taking stock of decisions reached at previous conferences and bringing research results to a wider group of higher education stakeholders. The research infrastructure findings will be shared at the COREVIP and related events.

Furthermore, the AAU meetings bring together not only university leaders but key higher education players including policy makers (including sector ministers from various countries); development partners (including World Bank; Carnegie Corporation; African Development Bank); alongside academics and researchers, who deliberate on pertinent issues relevant to African higher education. Results of the research infrastructures project will be shared and disseminated widely during the conferences, workshops, seminars, fora and other meetings.

Additionally, the AAU undertakes various capacity building initiatives (such as Graduate Training via partial and full Fellowship Programmes; Leadership and Management Development; Resource Mobilization; Quality Assurance; Scientific Proposal Writing; ICT; Webinars and AAU TV Programmes; Library and Knowledge Management) for the benefit of African higher education stakeholders. The AAU uses such avenues to strengthen the capacity of HEIs to address Africa's developmental challenges. The research infrastructure findings will be shared at these capacity building events.

Other dissemination avenues and channels for the research findings include:

1) AAU's website, newsletters (AAU and ACE), and TV Channel.

2) ACE Impact network of 54 ACEs in West and Central Africa, and 24 ACEs in Southern and Eastern Africa.

3) SGCI, HAQAA (Harmonization, Quality Assurance and Accreditation) Initiative, African Quality Assurance Network (AfriQAN), and others.

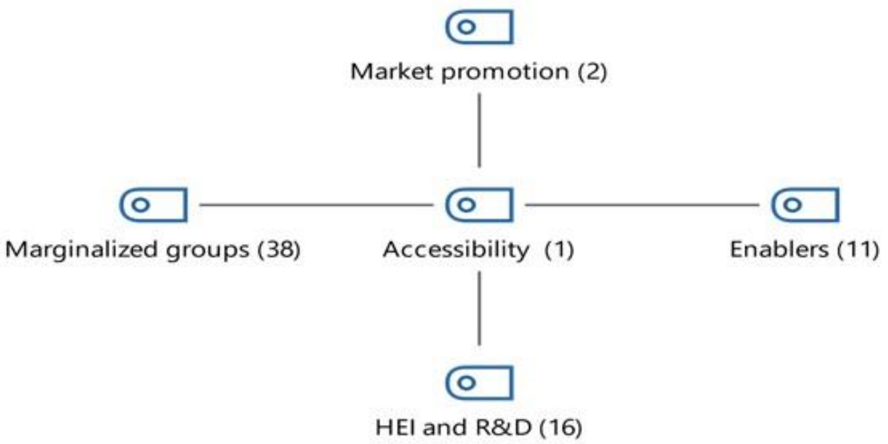
4) African Union Commission (AUC), Regional Economic Communities (RECs) such as Economic Community of West African States (ECOWAS), Southern African Development Community (SADC), ARUA, RUFORUM, and national platforms.

5) Programmes such as SAIS – involving six countries, a good platform.

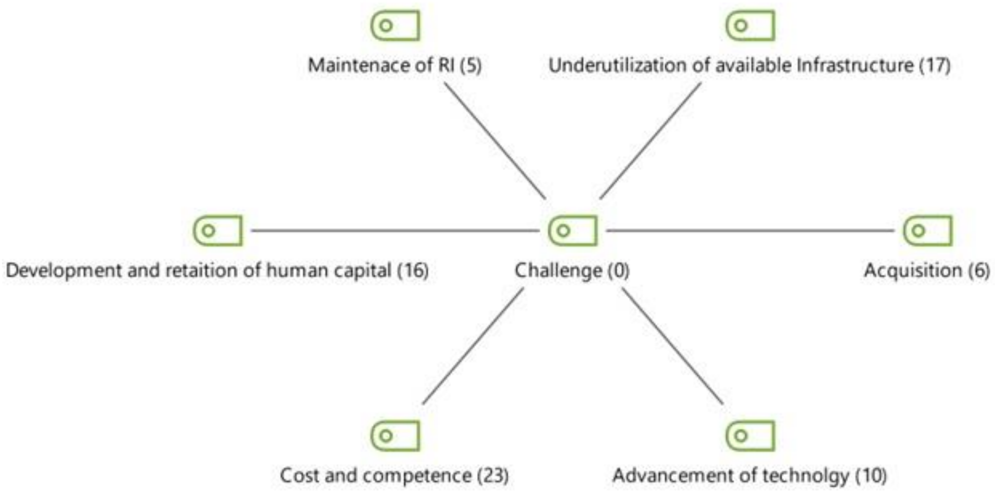
6) ATPS network that covers 5000 members in 52 countries.

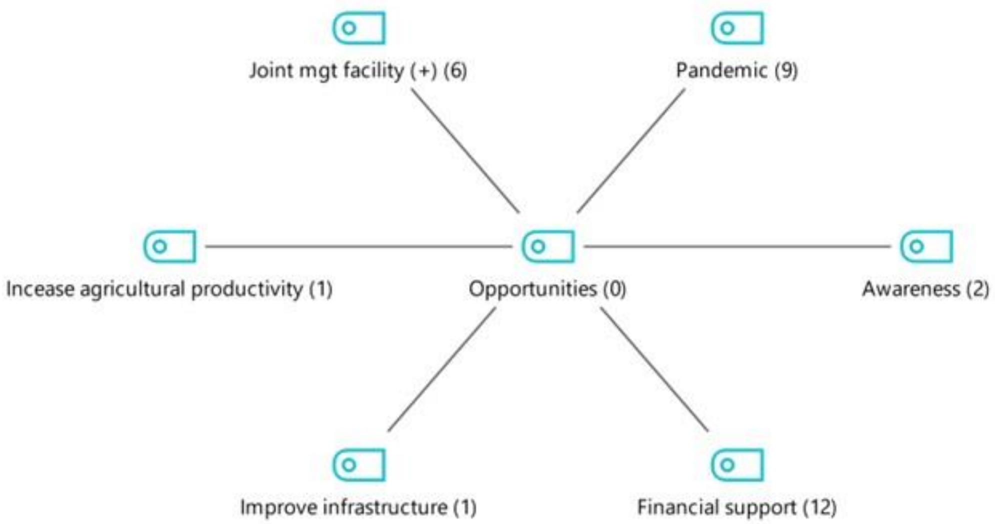
The salient features of the research infrastructures findings will be developed as peer-reviewed articles and sent to mainstream journals for possible publication. Policy briefs will also emanate from the results of the project and will be shared among key policy makers at national and institutional levels in Africa, as well as opinion leaders and development partners. The policy briefs will be instruments for high-level advocacy for necessary action and policy and programmatic interventions on research infrastructures in African countries.

Annex 2: Code Theory model for accessibility, challenges and opportunities



WP 3 team generated MAXQDA 20 models only for the codes on accessibility, challenges, and opportunities as they covered a larger part of the conversation.





Annex 3: Status of bandwidths provided by NRENS across Africa

Regional NRENs	*Country*	*NREN name*	*Number of Universities connected*	*% of universities connected*	*Range of bandwidth provided*
UbuntuNet Alliance (Eastern & Southern Africa)	Burundi	BERNET	13	-	38 Mbps
	Ethiopia [a]	EthERNet	36	-	100 Mbps
	Kenya	KENET	57	88%	-
	Madagascar	iRENALA	6	-	-
	Malawi	MAREN	3	-	-
	Mozambique	MoRENet	11	100%	34 – 155 Mbps
	Sudan	SudREN	35	100%	2 – 50 Mbps
	Tanzania	TERNET	7	-	8 – 15 Mbps
	Uganda	RENU	16	40%	5 – 200 Mbps
	Zambia	ZAMREN	7	60%	7.5 – 230 Mbps
WACREN (Western & Central Africa)	Côte d'Ivoire	RITER	5	-	100 Mbps
	Gabon	GabonREN	3	-	-
	Ghana	GARNET	25	28%	45 Mbps (Minimum)
	Niger	NigerREN	4	-	1 – 15 Mbps
	Nigeria	NgREN	27	100% (Almost)	155 Mbps basic in STM 1 increments
	Senegal	snRER	5	-	-
	Togo	SLREN	3	-	2 – 15 Mbps
ASREN (Middle East & North Africa)	Algeria	CERIST	63	-	10 – 100 Mbps
	Egypt	EUN	18	-	-

[a] More recent data from the draft ICT Strategic Plan for Higher Education in Ethiopia 2018 indicates that bandwidth ranges from 45 to 800 Mbps in Ethiopian universities.

Source: Bashir, 2020, http://documents1.worldbank.org/curated/en/337151607685646967/pdf/Connecting-Africa-s-Universities-to-Affordable-High-Speed-Broadband-Internet-What-Will-it-Take.pdf

Annex 4: Survey Instruments

This questionnaire seeks to investigate the current research infrastructure landscape, both physical and virtual, in Africa and the findings will be used to make recommendations to guide the formulation, implementation, and governance of an improved research infrastructure that sustains the science system on the continent. As a key stakeholder in higher education (HE); research and development; technical and vocational education and training (TVET); finance; industry; and allied sectors in Africa, we seek your contribution to this endeavor through providing appropriate responses to this questionnaire. All responses will be anonymized in the analysis and project publications. You will however be included in the distribution lists for the study outputs at the end of the study.

SECTION 1: Respondent details

1.1 Name (optional) Click here to enter text.
1.2 Organization Click here to enter text.
1.3 What is the size of your organisation (number of staff)? Click here to enter text.
1.4 How long (in years) has your organization been in operation? Click here to enter text.
1.5 What is your current position or rank in your organization? Click here to enter text.
1.6 How long (in years) have you been in this position? Click here to enter text.
1.7 Which country is your organization based in? Click here to enter text.
1.8 Please select the option that best describes your organizational affiliation.

R&D organization ☐
Higher education institution ☐
Industry organization ☐
Other governmental institutions ☐
Other non-governmental institutions ☐
International agencies ☐
Others (please specify) Click here to enter text. ☐

SECTION 2: Understanding the State of Research Infrastructure (RI) in Africa

2.1 In your opinion, what do you understand by RI? Click here to enter text.
2.2 Could you please list below up to five most important and **existing** physical and virtual RI that you are conversant with or aware of that support Higher Education Institutions (HEIs) and Research and Development (R&D) in Africa?

S/n	Physical Research Infrastructure	Virtual Research Infrastructure
1.		
2.		
3.		
4.		
5.		

2.3 Could you please list below up to five most important **emerging** physical and virtual RI that you are conversant with or aware of that support HEIs and Research in Africa:

S/n	Physical Research Infrastructure	Virtual Research Infrastructure
1.		
2.		
3.		
4.		
5.		

2.4 Kindly identify specific RI (existing and emerging) that can enable transformative change in the following selected sectors:

S/n	Agriculture and Food systems	Health and Medicines	Science, Technology, Engineering and Mathematics (STEM)
1.			
2.			
3.			
4.			
5.			
6.			
7			

2.5 Mention and describe any RI good practice or case study (including hard or soft research infrastructure) that you are aware of in your country Click here to enter text.

2.6 On a scale of 1 - 5, where 1 is the lowest and 5 is the highest extent, what is the current status of availability and use of the following RI in HEIs and R&D in your country?

Status of RI in HEIs and R&D in your country	1	2	3	4	5
ICTs in general in HEIs and R&D institutions					
Fourth Industrial Revolution (4IR) technologies and infrastructure					
Power (Electricity) supply					
Smart classrooms					
Internet connectivity (penetration and speed)					
Distance learning platforms such as MOOC,					
Infrastructure for incubation, fabrication laboratories (Fablabs), deep technology start-up companies (Deeptechs), Academic bas Entrepreneurship hubs, etc.					
Human capacity					
Maintenance culture on training infrastructure					
Learning operations during COVID-19 pandemic period					
Availability of scholarships for STEM education					
Others, please specify Click here to enter text.					

2.7 Overall, how would you rate the state of adequacy of RI in (SSA)?

S/n	Rating	Score	Tick one only
1.	Extremely adequate	5	
2.	Very adequate	4	
3.	Moderately adequate	3	
4.	Inadequate	2	
5.	Extremely inadequate	1	

2.8 List up to five top challenges that limit access, availability and use of RI for HE and R&D development in SSA?

S/n	Top challenges to RI development in your country
1.	
2.	
3.	
4.	
5.	

SECTION 3: Stakeholders in the RI ecosystem and their contributions towards its sustenance

3.1 Who are the major stakeholders in the RI ecosystem in your country? Kindly list their names in the various categories provided in the table below.

S/n	Government	Private Sector	Development partners	Philanthropies/ Foundations	NGOs/ Civil Society	Others (specify)
1.						
2.						
3.						
4.						
5.						
6.						
7.						
8.						
9.						
10.						

3.2 On a scale of 1 - 5, where 1 is e lowest and 5 is the highest extent, what is the extent of contribution (funding) to RI development in HEIs and R&D by the following stakeholders?

RI Stakeholders	Extent of Contribution				
	1	2	3	4	5
Government funding such as research funds and budgeta allocations					
Private sector/ industry contribution					
Public-private partnership					

Foundations and philanthropies					
Impact investors					
Non-governmental organisations (NGOs)					
International collaborative grants					
Charity organizations					
Patent buyouts					
Corporate funding					
Development partners					
Loans schemes					
Consultancy services					
Diaspora financing					
Others, please specify Click here to enter text.					
Others, please specify Click here to enter text.					

SECTION 4: State of Governance of RI in HEIs and R&D

4.1 What is the subsisting policy or regulatory framework governing RI development in HE and R&D in your country? Please mention the policy(ies) and the year(s) of enactment.

Click here to enter text.

4.2 On a scale of 1 - 5, where 1 is the lowest and 5 is the highest extent, what is the current status of RI governance in your country with respect to the issues highlighted in the table below?

Status of RI Governance in HE and R&D Institutions	**1**	**2**	**3**	**4**	**5**
Policies, strategies and frameworks exist that support RI development in your country					
The policies, strategies and frameworks are optimally implemented					
There is a functional monitoring, evaluation and learning framework for RI					
There is adequate capacity in the relevant institutions (ministries, departments and agencies) for the implementation of existing policies and programmes					
There are quality assurance mechanisms already put in place for RI to thrive in your country					
The current HEI curricula recognize RI development					
There are public-private partnerships in HEI and R&D for RI development					
The governance structure in HEIs is inclusive and equitable with consideratio for gender balance, people living with disability, and the vulnerable communities					
The RI takes cognizance of gender and equity issues					
The governance structure fully embraces ICT as a key driver in the HEIs and R&D sectors					
There is value for money in the investments in RI in HEIs and R&D					
Current state of HEIs and R&D is adequate to embrace the Fourth industrial Revolution (4IR)					

The current state of RI in HEIs and R&D is well aligned with regional qualifications and standards in the spirit of integration					
The RI in HEIs and R&D is well aligned with the African Continental Free Trade Area (AfCFTA) Agenda					
RI enable academic associations to serve as data points to tackle challenges related to HEIs and R&D					
RI has enabled increased collaboration with other institutions in Africa and beyond					
RI has enabled adequate linkage among government, industry and HEIs in your country					
RI has reduced the level of brain drain in HEIs and R&D in your country					
Others, please specify Click here to enter text.					

SECTION 5: Crosscutting Issues

5.1 On a scale of 1 - 5, where 1 is the lowest and 5 is the highest extent, to what extent do you agree with the following statements about RI development in HE and R&D systems in your country?

Level of agreement on cross cutting issues around RI development in HE and R&D Systems	**1**	**2**	**3**	**4**	**5**
There are policies in place that specifically support women participation HE and R&D fields					
There are special RI that encourage women participation in HE, STEM and R&D fields					
There is a pipeline of girls and women transitioning from primary through secondary to university training and R&D					
There is adequate alignment of research activities to national priorities					
The human resource capacity available in your country is adequate to support HE and R&D activities that lead to transformative change in the sector					
The RI available in HE and R&D institutions is adequate to support Postgraduate programmes (PhD & MSc)					
The poor RI in Africa affects students' enrolment in Postgraduate programmes (PhD & MSc)					
Brain drain of HEI researchers has been partly caused by inadequate RI in Africa					
The regional centers of excellence have significantly enhanced the capaci of institutions in delivering high quality training that address regior challenges facing development?					
There is a weak link between HEIs research priorities and industrial needs					
The private sector has significantly stimulated technology innovation, entrepreneurship and scientific research and development in your country					
The private sector has been a major contributor to scientific and technological breakthroughs in the country					

TVET institutions play crucial role in producing graduates withrequired ski to sustain economic transformation					
There should be a functional strategy that will enable TVET graduates transition into universities to pursue higher education in their STEM fields					
Lack of funding is a major issue affecting RI development in Africa					
Institutionalizing exchange programs in HESTI, R&D and Entrepreneurship within and outside Africa will promote knowled circulation and partnerships					
The current learning system has significantly accommodated indigenous knowledge and innovations					
The ICT system is adequate for learning in a COVID-19 era					
Knowledge exchange mechanisms such as co-location, R&D collaboration, etc. could promote learning, R&D and Entrepreneursh linkages with the industry					
Others, please specify Click here to enter text.					

SECTION 6: Strengthening RIs in Africa for Transformative Change

6.1 Kindly mention in your opinion, up to 5 best strategies for strengthening RI development for effective transformation in HE, STEM and R&D in your country

S/n	Strategies for strengthening RI development in your country
1.	
2.	
3.	
4.	
5.	

6.2 What in your opinion are the three top priority sectors for RI investment for transformative change in your country?

S/n	Top Priority Sectors for RI investment in your country
1.	
2.	
3.	

NB: Kindly indicate (by ticking) your willingness to participate in a follow-up expert interview on this research:

Yes	
No	

Annex 5: Experts Consulted – Focused Group Discussions

Organisation	Department	Country	Gender
University of Johannesburg the Research fellow	Department of Mechanical Engineering Science	South Africa	Male
National Technology Business Centre		Zambia	Male
University of Lagos	Department of Agricultural Economics	Nigeria	Male
International University of Management	Office of the Rector	Namibia	Male
Southern African Innovation Summit		South Africa	Female
University of Zambia	School of Nursing		Female
University of Yaounde		Cameroon	Female
University of Nigeria Nsukka	Department of Agricultural Extension	Nigeria	Female
University of Zimbabwe	Department of Economics and Development	Zimbabwe	Male
Private Sector Research Consultant/Part Lecturer	University of Lagos	Nigeria	Male

Annex 6: Interview questions

1. **Importance/ role of research infrastructure**: Could you mention tangible contributions RI has made to institutional, national, and regional development?
2. **Policies**: Are there institutional, national and regional policies that support/ promote RI? How? Elaborate with examples?
3. **Access**: What mechanisms facilitate/ enable equitable access to RI? Does ICT and AI improve or limit access? How and Why? Is there a disparity between rural and urban settings? Is this being addressed? How? Is the locale of HEIs and R&D; joint management facilities necessary when considering access? Why? Do marginalised groups have limited access to RI (youth, gender, disabled)? How can this be addressed?
4. **Opportunities**: What opportunities for enhancing existing utilisation and access to RI. Can you elaborate? (Possible responses - the role of technology, wicked challenges, pandemics, testbeds, e.g. COVID-19).
5. **Challenges**: What are the challenges for RI acquisition, maintenance and effective utilisation? Are the rapid changes in technology a challenge (SSA countries have low production competence)? Is the inability of SSA to acquire the latest RI (budget priority and availability) a limiting factor? Is the cost and competence to maintain RI facilities restricting? Is there a critical mass of human capital (particularly female scientists continuously developed and retained)? Is the pipeline for human capital robust and gender-balanced (supportive education policy for STEM)?
6. **Collaboration**: What is the level of engagement of non-traditional R&D actors such as the Private Sector, Civil Society, regional platforms/ centres of excellence, and research and innovation programmes in RI? With examples elaborate the effectiveness of Triple or multiple helix platforms/ networks.
7. **Sustainability**: Has RI been affected by COVID-19 as an example of a system shock? How? What measures/strategies/policies would be needed to prevent repeated effects and build resilience? What roles do governance and management play in the sustainability of RI? What internal and or external support would be needed to ensure sustainability?

Annex 7: Case Studies of RIs in the Centres of Excellence in Africa

The following guidelines were used to gather context-specific information around research infrastructure in six (6) selected Centers of Excellence (CoE) in Africa to generate this case study report.

1. **About the Centre of Excellence (CoE)**
    a. Brief background – country, location, number etc…
    b. The specific mandates (including vision, mission, goals and objectives…)
    c. Areas of focus – teaching, research, contribution to economic development (public good)
2. **Research Infrastructure (RI)**
    a. Understanding of RIs
    b. The State (availability, functionality and use) of physical and virtual RIs in the CoE
    c. Key achievements of the CoE in the past five years linked to the availability, functionality and use of RI in the Centre
    d. Major challenges limiting access, availability and use of RI in the CoE
    e. Major sources of funding for acquiring RI in the CoE
    f. The current state of RI governance and capacity in the use of RI in the CoE
3. **RIs for Transformative Change**
    a. Opportunities for strengthening RI development in the CoE
    b. Current practices (and opportunities for sharing) RIs at national and regional levels
    c. RIs and (development) impacts – contribution to social, economic and environmental…

ACE Centres – selected from the current ACE Development Impact[8]

The selected centres include emerging (The Gambia) and established (Ghana and Nigeria) ACEs[9]

[8] https://ace.aau.org/ace-impact-centers/

[9] Note: We focus on ACEs in West Africa. The goal is to obtain a general sense of how RIs feature and are understood in ACEs in STEM and related fields, rather than to be representative. A second guiding principle behind the selection of ACEs was the possibility and ease of access to collect the data, as the timeframe was very short (about two 2-4weeks), which also informed the selection of ACEs in English speaking countries.

Endnotes

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[i] Functional RIs expecially, but also knowledge of non-functional, and why this is the case, is important for implemented effective RI development and management strategies.
[ii] Such as, Ghana Tertiary Education Commission, in Ghana; or National Universities Commission [NUC], in Nigeria.
[iii] UNESCO, 2020. The response of Higher Education to COVID-19 - Higher Education in Africa: challenges and solutions through ICT, online training, distance education and digital inclusion, https://en.unesco.org/news/response-higher-education-covid-19-higher-education-africa-challenges-and-solutions-through-ict
[iv] We note that this is a ten-year old report, and that the situation may have changed. Future studies should seek to provide updated finding on this, supported by empirical evidence.
[v] See https://www.iita.org/about-iita/research-hubs-and-stations/ s
[vi] See https://www.afdb.org/en/the-high-5/light-up-and-power-africa-—-a-new-deal-on-energy-for-africa
[vii] See https://www.ifc.org/wps/wcm/connect/news_ext_content/ifc_external_corporate_site/news+and+events/news/cm-stories/cm-connecting-africa#page0
[viii] http://ei4africa.eu
[ix] https://v2.sherpa.ac.uk/id/repository/3479
[x] A single resource at a single location
[xi] A RI that is part of a network of distributed resources, such as ocean, earth or seafloor observatories
[xii] A mechanism for encouraging innovation, for example by purchasing a patent and placing it in the public domain to eliminate price monopolies and stimulate origical research. See for example, https://dash.harvard.edu/handle/1/3693705, https://academic.oup.com/qje/article-abstract/113/4/1137/1916997?redirectedFrom=fulltext or https://www.sciencedirect.com/science/article/abs/pii/S0167718716301084
[xiii] See https://www.asti.cgiar.org/about
[xiv] https://ace.aau.org/about-ace-impact/
[xv] Such as biotechnologies or synthetic biology / gene editing / bioengineering
[xvi] https://www.waccbip.org/overview/
[xvii] Formerly, the UK's Department for International Development (DfID)
[xviii] https://ace2.iucea.org/index.php/press/covid-updates
[xix] Science output rising, but some countries' yields still low, Wagdy Sawahel 17 February 2022, https://www.universityworldnews.com/post.php?story=20220214141713369
[xx] http://www.unesco.org/new/en/communication-and-information/portals-and-platforms/goap/access-by-region/arab-states/algeria/
[xxi] https://en.wikipedia.org/wiki/Science_and_technology_in_Morocco
[xxii] Combining Extremely adequate (2%), Very Adequate (3%) and Moderately adequate (34%) (see Figure 5)
[xxiii] Extremely inadequate (7%) and Inadequate (38%) (see Figure 5)
[xxiv] There is the need for further research to explore the links to RIs deeper.
[xxv] Making higher education work for Africa: Facts and figures (scidev.net)
[xxvi] https://answersafrica.com/venture-capitalists-africa.html
[xxvii] https://au.int/sites/default/files/documents/29958-doc-cesa_-_english-v9.pdf
[xxviii] Functional RIs expecially, but also knowledge of non-functional, and why this is the case, is important for implemented effective RI development and management strategies.
[xxix] Such as, Ghana Tertiary Education Commission, in Ghana; or National Universities Commission [NUC], in Nigeria.
[xxx] See for example, UKRI (n.d.), which focused on biological sciences, health and food sector; physical sciences and engineering, social sciences, arts and humanities sector, environment, energy and computing - https://www.ukri.org/wp-content/uploads/2020/10/UKRI-201020-LandscapeAnalysis-FINAL.pdf