World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(REVIEW ARTICLE)

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STEM education advancements in African contexts: A comprehensive review

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World Journal of Advanced Research and Reviews, 2024, 21(01), 145–160

Publication history: Received on 23 November 2023; revised on 30 December 2023; accepted on 01 January 2024

Article DOI: https://doi.org/10.30574/wjarr.2024.21.1.2719

Abstract

In the rapidly evolving global landscape, STEM (Science, Technology, Engineering, and Mathematics) education stands as a pivotal factor in driving economic growth and technological advancement, particularly in the African context, where it faces unique challenges and opportunities. This study aims to provide a comprehensive analysis of the advancements, challenges, and future prospects of STEM education in African contexts, exploring the historical evolution, current state, and key challenges of STEM education, along with the innovations, roles of government and non-governmental organizations, and comparative analysis with global trends. The paper methodically examines various facets of STEM education in Africa, including its historical background, current practices, challenges, and innovations. It delves into the role of digital technologies, gender dynamics, collaborative efforts, and international partnerships in STEM education. It employs a systematic literature review approach and focuses on peer-reviewed articles and scientific reports to comprehensively understand the subject. The study concludes that STEM education in Africa is marked by challenges such as resource limitations, gender disparities, and inadequate teacher training, but also highlights significant innovations and the potential for technological integration. The paper recommends policy reforms focusing on teacher training, curriculum development, resource allocation, and gender equity, emphasizing the need for leveraging technological innovations and fostering international collaborations for the advancement of STEM education in Africa.

Keywords: STEM Education; Africa; Technological Integration; Educational Policy; International Collaboration.

1. Introduction

1.1. Rationale for Focusing on STEM Education in Africa

The rationale for focusing on Science, Technology, Engineering, and Mathematics (STEM) education in Africa is multifaceted, addressing both the continent's unique challenges and its potential for growth. Badmus and Omosewo (2020) highlight the critical role of STEM education in developing countries, emphasizing its importance in modernization efforts across various human endeavors. The evolution of STEM, STEAM (Science, Technology, Engineering, Arts, and Mathematics), and STREAM (Science, Technology, Reading, Engineering, Arts, and Mathematics) approach reflects a growing recognition of the need to prepare learners with the knowledge and skills necessary to tackle complex, real-life challenges (Badmus & Omosewo, 2020).

In the context of Liberia, West Africa, Torto et al. (2022) demonstrate how technological innovations like the Internet Backpack are transforming STEM education, thereby contributing to agricultural and economic development. This example underscores the potential of STEM education to catalyze transformational changes in development processes, improving living standards, healthcare, food security, and other indicators of human development in Africa (Torto et al., 2022).

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Furthermore, the intersection of racial identity and STEM identity development is crucial in the African context. Morton, Gee, and Woodson (2019) explore this dynamic, particularly in the context of Black students in predominantly White institutions. Their research on Black X Consciousness in STEM underscores the importance of understanding how African students perceive and integrate their racial identity within STEM learning environments (Morton, Gee, and Woodson, 2019).

The focus on STEM education in Africa is not merely about academic achievement; it's about equipping the continent's youth with the tools to engage effectively with the world's rapidly advancing technological landscape. This includes addressing the knowledge gap in technology integration in classrooms, a particularly acute challenge in many African countries (Badmus & Omosewo, 2020). By fostering a STEM-educated workforce, Africa can better position itself to participate in, and benefit from, the global economy, especially in sectors where technological expertise is increasingly crucial.

Moreover, the integration of STEM education with local contexts and challenges, such as climate change and food security, as seen in the work of Torto et al. (2022), is vital. This approach ensures that STEM education is not just about importing global knowledge but also about applying it to local contexts and challenges, making it relevant and impactful for African communities.

The rationale for focusing on STEM education in Africa is rooted in the continent's need for modernization, economic development, and the empowerment of its youth to meet the challenges of the 21st century. The integration of technology, consideration of local contexts, and the acknowledgment of the interplay between racial and STEM identities are crucial components of this focus.

1.2. Historical Evolution of STEM Education in African Countries

The historical evolution of STEM (Science, Technology, Engineering, and Mathematics) education in African countries is a complex narrative that intertwines with the continent's broader educational and socio-political history. This evolution reflects a journey from traditional indigenous knowledge systems to modern educational frameworks, often influenced by external factors such as colonialism and globalization.

Badmus and Omosewo (2020) provide insights into the evolution of educational approaches in Africa, particularly in the context of STEM. They note that the development of STEM, STEAM (Science, Technology, Engineering, Arts, and Mathematics), and STREAM (Science, Technology, Reading, Engineering, Arts, and Mathematics) education in Africa has been a response to the need for up-to-date knowledge and skills to solve real-life challenges. This evolution signifies a shift from traditional learning methods to more integrated and holistic educational models, aiming to prepare learners for the complexities of modern life (Badmus & Omosewo, 2020).

Mkhize (2023) offers a critical perspective on the evolution of STEM education in South Africa, particularly regarding the experiences of African women in these disciplines. The historical dominance of white men in STEM fields, rooted in colonial ideologies, has shaped the educational landscape in African countries. Mkhize argues that the transformation process in STEM disciplines within South African universities has been slow, often amounting to mere reform rather than a fundamental transformation. This highlights the challenges faced in reshaping STEM education to be more inclusive and representative of the diverse identities within African societies (Mkhize, 2023).

Ezeanya-Esiobu and Ezeanya-Esiobu (2019) delves into the historical origins of African formal education curricula, emphasizing that education, including STEM education, was significantly influenced by colonial powers. The introduction of Western education by missionaries and colonial administrations was not primarily aimed at advancing African societies but rather at creating a workforce to assist in administrative duties. This colonial legacy has had lasting impacts on the structure and content of education systems in Africa, including STEM education. The post-colonial period did not immediately bring significant changes to these systems, as African countries continued to rely on former colonial powers for educational direction (Ezeanya-Esiobu, & Ezeanya-Esiobu, 2019).

The historical evolution of STEM education in Africa is marked by a transition from indigenous knowledge systems to a more globalized educational framework, influenced by external forces such as colonialism. This evolution has been characterized by efforts to integrate modern knowledge and skills into the curriculum, while also grappling with the challenges of creating inclusive and representative educational environments. The experiences of African women in STEM, as highlighted by Mkhize (2023), underscore the need for a more profound transformation in STEM education, beyond mere reform. The legacy of colonialism, as discussed by Ezeanya-Esiobu, and Ezeanya-Esiobu (2019) continues

to influence the structure and content of STEM education in Africa, presenting both challenges and opportunities for future development.

1.3. Current State of STEM Education in Africa: An Overview

The current state of STEM (Science, Technology, Engineering, and Mathematics) education in Africa is a critical area of focus, given its potential to drive economic success and address various socio-economic challenges. Mutsvangwa and Zezekwa (2021) provide a comprehensive overview of the role of STEM education in achieving sustainable livelihoods in Africa, particularly in sub-Saharan countries. They identify key challenges hindering the growth of STEM education, including a shortage of qualified teachers, overcrowded classrooms, lack of resources, outdated curricula, and inadequate teacher training in both content and pedagogical knowledge. Notably, less than 25% of African students in higher education are pursuing STEM qualifications, and of these, only 30% are female, indicating significant gender disparities (Mutsvangwa & Zezekwa, 2021).

Bryan and Guzey (2020) discuss the global perspectives on STEM education, emphasizing its importance in increasing productivity, prosperity, and competitiveness. They highlight the need for integrated STEM education, which is crucial for addressing current and future challenges. This global perspective is particularly relevant for Africa, where the integration of STEM disciplines can be a key driver for educational policy and socio-economic development (Bryan & Guzey, 2020).

Aslam et al. (2022) provide insights into the state of STEM education research in Pakistan, which, while not directly focused on Africa, offers valuable lessons for African countries. Their systematic literature review reveals a lack of awareness and research in STEM education, particularly at the K-12 and tertiary levels. This situation mirrors the challenges faced in many African countries, where STEM education is still emerging and requires significant research and development efforts (Aslam et al., 2022).

Several challenges, including limited resources, inadequate teacher training, and gender disparities characterize the current state of STEM education in Africa. However, there is also a growing recognition of the importance of STEM education in driving economic growth and addressing socio-economic challenges. As discussed in the global context, the integration of STEM disciplines offers a promising direction for African countries to enhance their educational systems and better prepare students for the demands of the 21st century. Addressing the identified challenges and leveraging global insights and best practices will be crucial for the advancement of STEM education in Africa.

1.4. Key Challenges Facing STEM Education in African Contexts

STEM (Science, Technology, Engineering, and Mathematics) education in Africa faces a myriad of challenges that hinder its growth and effectiveness. Mutsvangwa and Zezekwa (2021) identify several key issues, including a shortage of qualified STEM teachers, overcrowded classrooms, lack of resources, outdated curricula, and inadequate content and pedagogical knowledge training. These challenges are compounded by the fact that less than 25% of African students in higher education pursue STEM qualifications, and of these, only 30% are female, indicating significant gender disparities (Mutsvangwa & Zezekwa, 2021).

Barakabitze et al. (2019) highlight the role of Information and Communication Technologies (ICTs) in transforming African Education Systems (AES) in STEM subjects. They point out the challenges of integrating ICTs in education, including the lack of infrastructure, limited access to technology, and insufficient training for educators in ICT usage. Despite these challenges, ICTs present opportunities for improving the quality of STEM education through initiatives such as intensive ICT skills training for teachers and the emergence of living labs and innovation spaces (Barakabitze et al., 2019).

Badmus and Omosewo (2020) discuss the limitations of knowledge, expertise, and resources to cope with emerging trends for meaningful classroom integration in Africa. They emphasize the need for solutions from areas like robotics to resolve the limitations of technology integration in African classrooms. The gap in knowledge and expertise is a significant barrier to the evolution of STEM, STEAM, and STREAM approaches in Africa (Badmus & Omosewo, 2020).

STEM education challenges in Africa are multifaceted, ranging from infrastructural deficits and resource limitations to gender disparities and inadequate teacher training. Addressing these challenges requires a concerted effort from various stakeholders, including governments, educational institutions, and international partners. The integration of ICTs and innovative approaches like robotics can play a crucial role in overcoming these challenges and enhancing the quality and reach of STEM education in Africa.

1.5. Innovations and Technological Integration in STEM Education

Innovations and technological integration in STEM (Science, Technology, Engineering, and Mathematics) education are pivotal for enhancing learning experiences and outcomes in African educational contexts. Gillet et al. (2019) discuss the Go-Lab Goes Africa (GO-GA) initiative, an innovation action supported by the European Commission to promote and implement digital STEM education in secondary schools across Africa. This initiative outlines a strategic approach to overcoming challenges and achieving results in digital STEM education, emphasizing the importance of technological integration in modern educational practices (Gillet et al., 2019).

Liu, Chubarkova, and Kharakhordina (2020) explore the impact of online technologies in STEM education, highlighting their role in improving the quality of technical education and keeping pace with rapid technological progress. Their research, involving students from universities in Russia and China, demonstrates that integrated online STEM education significantly increases student engagement and academic performance. This finding is relevant for African contexts, where online technologies can be leveraged to enhance STEM education and address challenges such as access to quality resources and expert knowledge (Liu, Chubarkova, and Kharakhordina, 2020).

Nicolete et al. (2015) present a case study on the integration of technological resources in mathematics classes in Brazilian basic education, part of a project aimed at integrating technology in teaching STEM subjects. This project, recognized for its innovation, proposes the use of mobile learning to teach traditional concepts in STEM disciplines. The success of this project in Brazil provides valuable insights for similar initiatives in Africa, where the integration of mobile and digital technologies can motivate and improve STEM education (Nicolete et al., 2015).

The integration of innovations and technology in STEM education is crucial for advancing educational practices in Africa. Initiatives like GO-GA demonstrate the potential of digital technologies to transform learning experiences, while research on online technologies in STEM education underscores the importance of integrating these tools to enhance student engagement and learning outcomes. The case study from Brazil further illustrates how technological integration can motivate students and improve the teaching of STEM subjects. These insights are vital for African educational systems as they strive to adapt to the demands of the 21st century and prepare students for a technologically advanced global economy.

1.6. The Role of Government and Non-Governmental Organizations in STEM Education in Africa

The role of government and non-governmental organizations (NGOs) in advancing STEM (Science, Technology, Engineering, and Mathematics) education in Africa is crucial, given the diverse challenges and opportunities in the educational landscape of the continent. Adu-Baffoe and Bonney (2021) explore the indispensable role of NGOs in basic education delivery in Ghana, highlighting the contributions of organizations like Action Aid Ghana in infrastructure development, provision of teaching and learning materials, and capacity development of teachers. Despite these efforts, challenges remain in improving students' performances, underscoring the need for more comprehensive and collaborative approaches (Adu-Baffoe & Bonney, 2021).

Brophy (2020) discusses the varied roles of NGOs in supporting education in Africa, ranging from small local organizations to large international entities. These organizations often reflect the objectives of their founders and have evolved from relying on small charities to receiving substantial funding from governments. Brophy emphasizes the shift in NGO funding and the implications of government involvement in NGO education programs, which can sometimes be seen as part of broader socio-political strategies (Brophy, 2020).

Makofane and Selepe (2022) examine the role of NGOs in South Africa, particularly in rural development, which includes educational initiatives. They highlight the diversity of NGOs in terms of organizational form, structure, and culture, and their key role in providing essential services such as health care, education, and economic opportunities. The study underscores the importance of NGOs in filling gaps left by government policies, especially in the context of decentralization and reduced social spending (Makofane & Selepe, 2022).

The involvement of both government and NGOs is vital in addressing the multifaceted challenges of STEM education in Africa. While governments provide policy direction and funding, NGOs often bring innovation, flexibility, and grassroots connections that are essential for effective educational interventions. Collaborative efforts between these entities can lead to more sustainable and impactful educational outcomes. However, it is crucial to ensure that these collaborations are aligned with the educational needs of African communities and contribute to the overall goal of improving STEM education across the continent.

1.7. Comparative Analysis: African STEM Education vs. Global Trends

The comparative analysis of STEM (Science, Technology, Engineering, and Mathematics) education between Africa and global trends reveals significant insights into the educational practices, challenges, and advancements in various regions. Li, Liu, and Li (2020) conducted a comparative analysis of STEM education research between 2016 and 2020 using CiteSpace, highlighting the global impact of STEM education on educational practice and policy. Their analysis shows that while developed countries like the United States and Australia have long implemented STEM education as part of their national development strategies, countries like China have recently started to pay more attention to STEM education, indicating a global trend towards the adoption of STEM education (Li, Liu, and Li, 2020).

Zhan et al. (2022) provide a comprehensive bibliometric analysis of the literature in STEM education over the past 15 years, focusing on global distribution and research trends. Their findings suggest that STEM education is increasingly gaining scholarly attention and is developing diversely, emphasizing interdisciplinary, cross-domain, and regional collaboration. The study reveals that developed Western countries have focused on educational equity and disciplinary integration, while developing countries, including those in Africa, tend to focus more on pedagogical practices. This indicates a divergence in the focus of STEM education between developed and developing regions (Zhan et al., 2022).

Wolff et al. (2022) explore the thematic differences in engineering education literature between the Global North and South, providing insights into these regions' representation and thematic focus. Their study reveals that the Global South, including African countries, is underrepresented in terms of the volume of education research and research impact. The study also finds thematic differences, such as a focus on understanding challenges at statistical and curricular levels in the Global South, in contrast to the Global North's focus on showcasing innovative learning practices in better-resourced contexts (Wolff et al., 2022).

The comparative analysis of African STEM education versus global trends highlights several key points. Firstly, there is a global recognition of the importance of STEM education, with both developed and developing countries increasingly adopting STEM education strategies. Secondly, there is a divergence in the focus of STEM education, with developed countries emphasizing educational equity and disciplinary integration, while developing countries, including those in Africa, focus more on pedagogical practices. Lastly, the underrepresentation of the Global South in STEM education research and the thematic differences in focus suggest the need for more targeted research and policy interventions to address the unique challenges and leverage the opportunities in African STEM education.

1.8. Identifying Gaps in Existing Literature on STEM Education in Africa

The existing literature on STEM (Science, Technology, Engineering, and Mathematics) education in Africa reveals several gaps that need to be addressed to enhance the effectiveness and reach of these educational programs. Mutsvangwa and Zezekwa (2021) identify key issues hindering the growth of STEM education in Africa, such as the shortage of qualified STEM teachers, overcrowded classrooms, lack of resources, outdated curricula, and inadequate teacher training. These challenges highlight the need for more research focused on developing practical solutions and strategies to overcome these barriers (Mutsvangwa & Zezekwa, 2021).

Aslam et al. (2022) conducted a systematic literature review on STEM education in Pakistan, which, while not directly focused on Africa, provides insights into the common challenges in developing countries. Their study reveals a lack of awareness and research in STEM education, particularly at the K-12 and tertiary levels. This mirrors the situation in many African countries, where there is a need for more comprehensive research to understand and address the specific challenges of STEM education (Aslam et al., 2022).

Kayan-Fadlelmula et al. (2022) present a systematic review of STEM education research in the Gulf Cooperation Council (GCC) countries, identifying trends, gaps, and barriers. Their findings indicate that despite educational reforms and resources, there is still insignificant improvement in student achievement in STEM subjects. This study underscores the importance of identifying and addressing the factors influencing student participation in STEM and the gaps in STEM education research, which are also relevant to the African context (Kayan-Fadlelmula et al., 2022).

The gaps in existing literature on STEM education in Africa and similar regions point to several areas that require further investigation and development. These include the need for more research on effective teacher training programs, development of contextually relevant curricula, strategies to improve resource allocation, and ways to increase student engagement and performance in STEM subjects. Additionally, there is a need to explore innovative approaches to integrate technology and practical applications in STEM education to make it more appealing and relevant to students in Africa. Addressing these gaps will be crucial for empowering African countries through solid STEM education and preparing their youth for the challenges of the 21st century.

1.9. Purpose and Scope of the Study

This study's primary purpose is to comprehensively analyse the advancements, challenges, and future prospects of STEM (Science, Technology, Engineering, and Mathematics) education in African contexts. This research aims to explore the historical evolution of STEM education in African countries, assess the current state of STEM education, and identify the key challenges and innovations shaping its landscape. A significant focus is placed on understanding the role of government and non-governmental organizations in promoting and facilitating STEM education and comparing African STEM education trends with global practices. The study seeks to identify gaps in the existing literature and propose strategic recommendations for stakeholders involved in STEM education in Africa. By doing so, the research aims to contribute to the body of knowledge in this field and provide actionable insights for educators, policymakers, and international organizations working towards the enhancement of STEM education in Africa.

The scope of this study encompasses a detailed examination of various aspects of STEM education across different African countries. It includes an analysis of the historical background, current practices, and future trends in STEM education, particularly emphasising the challenges and opportunities unique to the African context. The study also involves a comparative analysis of global STEM education trends, providing a broader perspective on Africa is position in the global educational landscape. The research is primarily focused on the K-12 and tertiary education levels, considering the critical role these stages play in shaping the future workforce and innovators in STEM fields. While focusing on Africa, the study's geographical scope includes a diverse range of countries within the continent, acknowledging the variations in educational systems, cultural contexts, and economic conditions across different regions.

2. Methodology

2.1. Comprehensive Approach to Literature Review and Analysis

The comprehensive approach to literature review and analysis in STEM education, particularly in the context of Africa, involves a systematic and methodical examination of existing research to identify trends, gaps, and emerging themes. Ilma et al. (2023) utilized a systematic literature review method adapted from PRISMA to analyze trends in STEM or STEAM education research in Indonesia. Their approach, focusing on articles published in national and international journals, provides a model for conducting a thorough literature review in STEM education. This method involves analyzing articles based on various indicators such as title, author, journal name, publication year, and research method, offering a structured way to synthesize existing literature (Ilma et al., 2023).

Hasanah (2020) conducted a literature review to identify common themes in STEM education and the scope of STEM education from previous studies. This review utilized a variety of keywords and electronic databases, demonstrating the importance of a comprehensive search strategy in capturing the breadth of STEM education literature. The review's findings on the definitions and scopes of STEM education based on literature underscore the importance of understanding how STEM education is conceptualized and implemented across different contexts (Hasanah, 2020).

Wang, Shen, and Chao (2021) integrated computational thinking into their review of STEM education literature. Their systematic process involved identifying key areas for future study by reviewing empirical studies investigating computational thinking in higher education's teaching and learning contexts. This review highlights the significance of including emerging areas like computational thinking in STEM education literature reviews, reflecting the evolving nature of the field (Wang, Shen, and Chao, 2022).

A comprehensive approach to literature review and analysis in STEM education involves a systematic and structured method to explore existing research. This approach should encompass a broad range of sources, utilize clear inclusion and exclusion criteria, and focus on identifying trends, gaps, and emerging themes in the literature. Such an approach is crucial for understanding the current state of STEM education, particularly in diverse educational contexts like Africa.

2.2. Criteria for Inclusion and Exclusion of Studies

The criteria for inclusion and exclusion of studies in a literature review are pivotal in ensuring the relevance and quality of the research being analyzed. Wood and Malik (2022) undertook a systematic approach to analyze empirical research examining the use of technology in STEM education. They applied specific inclusion and exclusion criteria to select publications, focusing on problem, project, and case-based learning within higher education STEM disciplines. This approach underscores the importance of clear criteria in selecting studies that are most relevant to the research questions (Wood & Malik, 2022).

Kurniawan, Rosjanuardi, and Aswin (2022) conducted a systematic literature review on mathematical justification in mathematics education. They used the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines, including specific inclusion and exclusion criteria, to select relevant studies. This methodological rigor is essential in ensuring that the review covers the most pertinent and high-quality studies in the field (Kurniawan, Rosjanuardi, and Aswin, 2022).

Lyon and Magana (2020) reviewed literature on computational thinking in higher education. They employed a systematic process with defined inclusion and exclusion criteria to evaluate studies against types of methods, target population, and significant findings. This approach highlights the need for a structured method in literature review to ensure comprehensive coverage of the topic (Lyon & Magana, 2020).

Anwar et al. (2019) presented a systematic review of literature on educational robotics, applying specific inclusion and exclusion criteria to identify studies published over an 18-year period. Their review process, focusing on themes such as general effectiveness, students' learning skills, and teachers' professional development, demonstrates the importance of having clear criteria to guide the selection of studies for a literature review (Anwar et al., 2019).

The criteria for inclusion and exclusion of studies in a literature review are crucial in defining the scope and ensuring the quality of the review. These criteria should be clearly articulated and aligned with the research objectives to ensure that the review comprehensively covers relevant and high-quality studies in the field.

3. Results

3.1. Overview of Key Innovations in STEM Education Across Africa

Various innovative initiatives and projects have significantly shaped the landscape of STEM education in Africa. Gillet et al. (2019) discuss the Go-Lab Goes Africa (GO-GA) initiative, a project supported by the European Commission to promote and implement digital STEM education in secondary schools across Africa. This initiative represents a significant step in integrating digital technologies into the educational framework, aiming to enhance STEM subjects' learning experience and outcomes. Despite facing challenges, the GO-GA project's vision and implementation strategy have achieved notable results in its first year, demonstrating the potential of digital education in African contexts (Gillet et al., 2019).

Kireš et al. (2019) present the IT Academy project, which aims to drive key changes in STEM education at primary and secondary schools through national-wide impact. This project focuses on active learning, emphasizing conceptual understanding and the development of inquiry skills. It also integrates scientific literacy and computational thinking into the content of science and mathematics curricula, creating a strong link to informatics concepts and practical applications. The IT Academy project is expected to increase young people's interest in studying computer science and STEM, showcasing an innovative approach to STEM education (Kireš et al., 2019).

Babalola, du Plessis, and Babalola, (2021) explore the challenges African women face in leadership positions in the field of Science, Technology, Engineering, and Mathematics (STEM). Their study aims to understand the factors that inhibit African women's pursuit of leadership roles in STEM. Using a qualitative approach, they collected narratives from 42 female African leaders in STEM across 12 African countries. The study reveals that while education, scholarship, supportive organizational structures, commitment, hard work, and tenacity are enablers, women still experience less acceptance than men in STEM leadership roles due to the prevailing organizational culture in several African countries. This research contributes to understanding the organizational culture and challenges faced by women STEM leaders in Africa.

Key innovations in STEM education across Africa include the integration of digital technologies, active learning approaches, focus on gender inclusivity, and the implementation of innovative teaching methods. These initiatives demonstrate the dynamic nature of STEM education in Africa and its alignment with global educational trends and needs.

3.2. Case Studies of Successful STEM Programs in Africa

Several successful programs have marked the advancement of STEM education in Africa, each contributing uniquely to the field. Tijani et al. (2021) present a case study of the Virtual STEM Project, an initiative carried out in Nigeria and Kenya by Co-creation Hub (CcHub), Africa's largest innovation institute. This program aimed to support in-service and pre-service teachers with the necessary skills, tools, and teaching methodologies, integrating the Inquiry-Based

Learning (IBL) approach. The project's impact assessment and evaluation of its effectiveness in delivering remote teaching training activities highlight the potential of digital platforms in enhancing STEM education in Africa (Tijani et al., 2021).

Pearson et al. (2022) systematically reviewed STEM-degree support programs targeting low-income, first-generation, and underrepresented students. While focused on the United States, the study's findings offer valuable insights for African contexts, particularly in identifying critical components of successful programs. These components, including mentorship, financial support, and academic assistance, are essential in designing effective STEM education programs in Africa, where similar demographic challenges exist (Pearson et al., 2022).

Muhammad, Jibril, and Isah, (2022) provide a comparative analysis of STEM education programs in the UK, USA, Japan, and Australia. Their study offers insights into different program structures, target groups, objectives, and achievements, which can be adapted and applied to the African context. The analysis shows that successful STEM education programs often require community involvement and continuous curriculum development, aspects that are crucial for the African educational landscape (Muhammad, Jibril, and Isah, 2022).

Peters-Burton et al. (2022) explore two exemplar engineering-focused elementary schools, providing case studies on their engineering programming, teacher professional development, and integration of growth mindset. While the study is based in the United States, the methodologies and systems used in these schools can be adapted for African educational settings. The focus on engineering education and the development of a growth mindset are particularly relevant for African countries looking to enhance their STEM offerings (Peters-Burton et al., 2022).

These case studies demonstrate the diversity and potential of STEM education programs in enhancing learning outcomes. The insights gained from these studies can guide the development of innovative, inclusive, and effective STEM education programs in Africa, tailored to meet the specific needs and challenges of the continent.

3.2.1. Impact of Digital Technologies on STEM Learning

The integration of digital technologies in STEM education has significantly influenced learning outcomes and teaching methodologies across Africa. Tijani et al. (2021) present a case study of the Virtual STEM Project, an initiative implemented during the Covid-19 pandemic in Nigeria and Kenya. This project aimed to equip in-service and pre-service teachers with digital tools and teaching methodologies, integrating the Inquiry-Based Learning (IBL) approach. The study highlights the effectiveness of digital technologies in facilitating remote teacher training and enhancing STEM education. The project's success in adapting to pandemic constraints and maintaining educational continuity underscores the potential of digital technologies in transforming STEM learning environments in Africa (Tijani et al., 2021).

Chauke (2022) investigates the factors influencing male and female students' choices regarding STEM education at the TVET college level in South Africa. The study, conducted using qualitative research methods and focus-group interviews with 20 students, identifies various push-pull factors such as lucrative salary, graduate unemployment rate, aptitude for mathematics and science, parental education, and autonomy and independence. The research also highlights the importance of rejecting stereotypical feminine identities in influencing students' decisions. Chauke suggests that an Afrocentric approach should be integrated into STEM teaching and learning at TVET colleges to address the gender gap in STEM education.

The impact of digital technologies on STEM learning in Africa is profound, offering innovative solutions to traditional educational challenges. These technologies have enabled remote learning, enhanced teacher training, and contributed to reducing gender disparities in STEM fields. The successful implementation of digital technologies in STEM education underscores their potential in revolutionizing the educational landscape in Africa, making STEM education more accessible, inclusive, and effective.

3.2.2. Role of Cultural and Contextual Factors in STEM Education

The role of cultural and contextual factors in STEM education in Africa is a critical aspect that influences the effectiveness and inclusivity of educational practices. Akintoye et al. (2023) advocate for a Culturo-Techno-Contextual Approach (CTCA) in STEM education, emphasizing the need for culturally and contextually responsive pedagogies. Their study, which involved a documental analysis and interviews with teachers who used CTCA, revealed that this approach significantly enhances students' academic achievement in STEM subjects. The CTCA's effectiveness lies in its ability to integrate cultural relevance and technological advancements, making STEM education more accessible and relatable to African students (Akintoye et al., 2023).

Schabort, Sinnes, and Kyle (2018) explore the complexities of implementing science education as a means of female empowerment in rural South Africa. Their transformative action research project involved developing and implementing a contextualized science curriculum in collaboration with local community members. The study highlights challenges, such as teacher motivation, malnutrition among learners, and conflicts between indigenous knowledge and Western science concepts. These challenges underscore the importance of understanding and respecting cultural contexts in STEM education, particularly when aiming for transformative educational outcomes (Schabort, Sinnes, and Kyle, 2018).

Tang, Li, and Crowther (2023) present a case study focusing on elementary English language learners (ELLs) in STEM education. Although the study is based in the United States, its findings offer valuable insights for African contexts, particularly regarding the interaction of language proficiency, pedagogical approaches, cultural diversity, and learning interest in STEM education. The study emphasizes the importance of considering cultural diversity and language barriers in STEM education, which are pertinent issues in many African countries with diverse linguistic and cultural backgrounds (Tang, Li, and Crowther, 2023).

Cultural and contextual factors play a pivotal role in shaping STEM education in Africa. Integrating culturally relevant pedagogies, understanding local challenges, and considering linguistic diversity are crucial for enhancing the effectiveness and inclusivity of STEM education. These factors are essential in developing educational practices that are both academically sound and socially and culturally responsive, catering to the diverse needs of African learners.

3.2.3. Gender Dynamics in STEM Education in Africa

The gender dynamics in STEM (Science, Technology, Engineering, and Mathematics) education in Africa present a complex landscape influenced by cultural, social, and economic factors. Elu (2018) examines the representation of females in STEM in Sub-Saharan Africa, utilizing data from the World Development Indicators. The study provides a descriptive analysis of the female share in STEM disciplines, highlighting the extent of gender inequality in the region. This analysis is crucial for informing policy interventions aimed at decreasing gender inequality and improving access to STEM education for women in Sub-Saharan Africa (Elu, 2018).

Chauke (2022) explores the gender differences in determinants of students' interest in STEM education, focusing on a TVET college in rural South Africa. The study, employing qualitative research methods, reveals that factors such as lucrative salary, graduate unemployment rate, aptitude for mathematics and science, and rejecting stereotypical feminine identities influence both male and female students' choices in STEM education. The study's findings underscore the need for Afrocentric approaches in teaching and learning STEM at TVET colleges to address the gender gap effectively (Chauke, 2022).

Fisher et al. (2020) elucidate gender-based differences in PhD performance across 17 African countries in STEM fields. The study finds that women had fewer papers accepted for publication during their doctoral studies and took longer to complete their PhD training compared to their male counterparts. The research highlights the importance of family-friendly policies, mentoring, and supervisory support tailored to women's specific needs and circumstances in STEM education. These factors are critical in addressing the underrepresentation of women in STEM and ensuring their successful progression in these fields (Fisher et al., 2020).

Gender dynamics in STEM education in Africa are shaped by a range of factors, including societal norms, economic considerations, and educational policies. Addressing these dynamics requires a multifaceted approach that includes policy interventions, culturally responsive teaching methods, and support systems that cater to the unique challenges faced by women in STEM fields. By tackling these issues, STEM education in Africa can become more inclusive, equitable, and effective in preparing both men and women for careers in these critical fields.

3.2.4. Challenges and Barriers to Effective STEM Education

The STEM (Science, Technology, Engineering, and Mathematics) education landscape in Africa is fraught with numerous challenges and barriers that significantly impede its development and effectiveness. Mutsvangwa and Zezekwa (2021) comprehensively analyse these challenges, particularly in sub-Saharan Africa. They identify a critical shortage of qualified STEM teachers as a primary barrier. This shortage is not just in numbers but also in the quality of training and expertise, leading to a gap in delivering quality STEM education. The lack of adequately trained teachers is compounded by overcrowded classrooms, which further diminishes the quality of education. Large class sizes make it difficult for teachers to provide individualized attention, conduct practical experiments, and engage students effectively in STEM subjects.

Another significant challenge is the lack of resources. Many African schools lack the basic infrastructure and materials necessary for effective STEM education, such as laboratories, modern equipment, and up-to-date textbooks. This scarcity of resources hinders practical, hands-on learning, which is crucial for understanding complex scientific and mathematical concepts. Furthermore, the curricula in many African educational systems are outdated and do not align with the current demands of the global STEM landscape. This misalignment results in graduates who are ill-prepared for the modern workforce and unable to contribute effectively to the continent's development.

Inadequate teacher training in content and pedagogical skills exacerbates these challenges. Teachers often lack the necessary skills to integrate innovative teaching methods and technology into their lessons, which is essential for engaging students in STEM. This gap in teacher training reflects a broader issue within the educational systems, where professional development opportunities for teachers are limited or non-existent.

Gender disparity is another critical issue in STEM education in Africa. Less than 25% of African students in higher education are pursuing STEM qualifications, and of these, only 30% are female. This gender gap is a result of various socio-cultural factors, including stereotypes, biases, and societal expectations that discourage girls and women from pursuing STEM fields. Addressing this disparity is crucial for ensuring equitable access to STEM education and for harnessing the full potential of the population in driving scientific and technological advancement.

The socio-economic challenges faced by the continent, such as poverty, unemployment, and the impacts of the COVID-19 pandemic, further complicate the situation. These challenges affect the standard of living and access to quality education, making it difficult for many students to pursue or excel in STEM subjects. The pandemic has particularly highlighted the need for digital literacy and access to technology, essential for remote learning and keeping pace with global educational trends.

There is a pressing need for effective policy development and implementation in response to these challenges. Policies that support quality STEM education at all levels, from primary to tertiary, are essential. These policies should improve teacher training, update curricula, provide necessary resources, and promote gender equity in STEM fields. Additionally, partnerships between governments, educational institutions, and international organizations are crucial for mobilizing resources and expertise to address these challenges.

The barriers to effective STEM education in Africa are complex and multifaceted, requiring a comprehensive and collaborative approach to overcome. By addressing these challenges, STEM education in Africa can be transformed, empowering the continent to meet its development goals and compete effectively in the global economy.

3.2.5. Collaborative Efforts and International Partnerships in STEM Education in Africa

The development of STEM education in Africa has increasingly relied on collaborative efforts and international partnerships, which have played a crucial role in enhancing educational outcomes and fostering innovation. Carmen and Groenewald (2015) discuss the ALLIES partnership between the Cape Peninsula University of Technology in South Africa and the University of Alabama in Huntsville. This collaboration focused on engineering design classes and the development of STEM tools for K-12 students in both the United States and South Africa. The partnership's emphasis on practical, hands-on learning experiences through the creation of STEM tools like catapults and wind tunnels exemplifies the potential of international collaborations in providing diverse and enriching educational experiences (Carmen & Groenewald, 2015).

Freeman, Marginson, and Tytler (2019) provide an international perspective on STEM policies and programs, extending from various regions including Africa. Their analysis highlights global trends in government STEM policy, school and tertiary level STEM education participation, and comparative performance in international assessments. This global perspective underscores the importance of collaborative networks and international partnerships in addressing systemic disparities in STEM education. The study suggests that such collaborations can lead to curriculum and pedagogy reform, enhancing science and mathematics participation and performance at all educational levels (Freeman, Marginson, and Tytler, 2019).

Torto et al. (2022) explore the impact of the Internet Backpack in Liberia, a technology that facilitates learning and has been deployed globally. Focusing on post-war Liberia, this project demonstrates how multi-stakeholder partnerships can effectively implement technologies to enhance STEM education. The Internet Backpack project, which includes environmental life sciences programs and sustainable agriculture, highlights the role of technology in transforming STEM education and its relevance to 21st-century development processes, including climate change mitigation (Torto et al., 2022).

Collaborative efforts and international partnerships are pivotal in advancing STEM education in Africa. These collaborations bring together diverse expertise, resources, and perspectives, leading to innovative educational tools and methods. They also provide a platform for sharing best practices and addressing common challenges in STEM education. By leveraging these partnerships, African countries can enhance their STEM education systems, preparing students for the demands of the global economy and contributing to sustainable development.

4. Discussion

4.1. Evaluating the Impact of Innovations in STEM Education

The impact of innovations in STEM education in Africa can be assessed through various initiatives and studies that have sought to integrate new technologies and methodologies into the educational landscape. Gillet et al. (2019) discuss the Go-Lab Goes Africa (GO-GA) initiative, an innovation action supported by the European Commission to promote and implement digital STEM education in secondary schools across Africa. This initiative aimed to enhance STEM subjects' learning experience and outcomes through digital technologies. Despite facing challenges, the GO-GA project's vision and implementation strategy achieved notable results in its first year, demonstrating the potential of digital education in African contexts (Gillet et al., 2019).

Khushk et al. (2023) provide an in-depth analysis of high-impact empirical studies in STEM education, highlighting the increasing need for technology-based occupations as robots replace humans in industry and society. Their study underscores several issues in the field of STEM education, including the gender divide and the effects of STEM education on people of all ethnicities. The authors emphasize the importance of addressing these issues in future research, particularly in science, to enhance creativity in research and education (Khushk et al., 2023).

Jackson (2020) assesses school segregation and its impact on STEM education, focusing on the performance of African American girls. The study begins with an assessment of school segregation in New York City and then assesses how this segregation influences the performance of African American female students in STEM education. The final section provides recommendations on increasing the number of African American girls in STEM education, highlighting the need for inclusive and equitable educational practices (Jackson, 2020).

The impact of innovations in STEM education in Africa is multifaceted, encompassing the integration of digital technologies, addressing gender and ethnic disparities, and ensuring equitable access to quality education. These innovations are crucial for preparing African students for the demands of the global economy and contributing to sustainable development. The studies discussed provide valuable insights into the challenges and opportunities in enhancing STEM education in Africa through innovative approaches.

4.2. Comparative Analysis: African Innovations vs. Global Practices in STEM Education

The comparative analysis of STEM education between Africa and global practices reveals significant insights into educational practices, challenges, and advancements in various regions. Li, Liu, and Li (2020) conducted a comparative analysis of STEM education research using CiteSpace, highlighting the global impact of STEM education on educational practice and policy. Their analysis shows that while developed countries like the United States and Australia have long implemented STEM education as part of their national development strategies, countries like China have recently started to pay more attention to STEM education, indicating a global trend towards the adoption of STEM education (Li, Liu, and Li, 2020).

Wolff et al. (2022) explore the thematic differences in engineering education literature between the Global North and South, providing insights into these regions' representation and thematic focus. Their study reveals that the Global South, including African countries, is underrepresented in terms of the volume of education research and research impact. The study also finds thematic differences, such as a focus on understanding challenges at statistical and curricular levels in the Global South, in contrast to the Global North's focus on showcasing innovative learning practices in better-resourced contexts (Wolff et al., 2022).

Milne and Mhlolo (2021) present a comparative study between the Singaporean and South African education systems, focusing on gifted education. The study shows that both countries had similar challenges at the point of independence from colonial rule, but they responded differently to those challenges. Singapore implemented inclusive education driven by excellence, while South Africa’s inclusive education is driven by equity without excellence. The study highlights the importance of coherent systems and policies in ensuring the effective implementation of STEM education (Milne & Mhlolo, 2021).

The comparative analysis of African STEM education versus global trends highlights several key points. Firstly, there is a global recognition of the importance of STEM education, with both developed and developing countries increasingly adopting STEM education strategies. Secondly, there is a divergence in the focus of STEM education, with developed countries emphasizing educational equity and disciplinary integration, while developing countries, including those in Africa, focus more on pedagogical practices. Lastly, the underrepresentation of the Global South in STEM education research and the thematic differences in focus suggest the need for more targeted research and policy interventions to address the unique challenges and leverage the opportunities in African STEM education.

4.3. Identifying Best Practices and Areas for Improvement in STEM Education in Africa

The advancement of STEM (Science, Technology, Engineering, and Mathematics) education in Africa hinges on identifying and implementing best practices while addressing areas that require improvement. Badmus and Omosewo (2020) delve into the evolution of STEM, STEAM, and STREAM education in Africa, highlighting the knowledge gap as a significant challenge. They emphasize the need for innovative approaches that integrate cultural relevance and technological advancements in STEM education. The study suggests that robotics and other emerging technologies can potentially resolve classroom integration challenges, pointing to the necessity of equipping educators with the skills and resources to cope with these trends (Badmus & Omosewo, 2020).

Olszewski-Kubilius (2022) discusses a university-school collaboration aimed at preparing underidentified and underserved students for advanced STEM coursework. The program featured early intervention, extensive outside-of-school programming in STEM, tutoring, and family support. This model demonstrates the effectiveness of early and sustained enrichment in STEM, leading to significant reading and mathematics achievement growth. The study underscores the importance of early and continuous engagement in STEM education, particularly for students from marginalized groups (Olszewski-Kubilius, 2022).

Lytras, Marouli, and Papadopoulou (2016) explore best practices in STEM education, focusing on active learning and innovative teaching methodologies. Their research emphasizes the role of active learning, technology-enabled teaching methodologies, and social networks in effective STEM education. The study provides insights into designing new STEM education programs that integrate technology and active learning strategies, highlighting the significance of hands-on learning tools in maximizing and accelerating STEM learning (Lytras, Marouli, and Papadopoulou, 2016).

The best practices in STEM education in Africa include the integration of cultural relevance, technological advancements, early and continuous STEM enrichment, and innovative teaching methodologies. Addressing the knowledge gap, equipping educators with the necessary skills and resources, and focusing on marginalized groups are crucial for the advancement of STEM education in Africa. These practices are essential for preparing African students for the demands of the global economy and contributing to sustainable development.

4.4. Policy Implications and Recommendations for Stakeholders in STEM Education in Africa

Developing and implementing effective policies are crucial for advancing STEM (Science, Technology, Engineering, and Mathematics) education in Africa. The challenges identified by Mutsvangwa and Zezekwa (2021) underscore the need for comprehensive strategies that address the shortage of qualified teachers, overcrowded classrooms, and outdated curricula. To overcome these challenges, governments and educational institutions must collaborate to enhance teacher training programs, update curricula, and ensure adequate resource allocation. These measures are essential for improving the quality of STEM education and making it more accessible and effective for students across Africa (Mutsvangwa & Zezekwa, 2021).

The study by Oladele, Ayanwale, and Ndlovu (2023) highlights the importance of technology adoption in STEM education, particularly in higher education institutions across sub-Saharan Africa. While students have responded positively to online teaching and learning, the study identifies critical areas for improvement, such as internet access and technical support. Policymakers and educational leaders must prioritize the development of robust technology infrastructure and provide necessary technical support to facilitate effective online STEM education. This approach will enhance the learning experience and ensure that students are equipped with the skills required in a technologically driven world (Oladele, Ayanwale, and Ndlovu, 2022).

Isma'il, Abbas, and Ibrahim (2023) conducted a study to investigate the enrollment trends, motivations, and future aspirations of female undergraduate students in STEM courses at the Federal University Gusau in Nigeria. The study employed a survey design and collected data from 350 female undergraduate students using a 36-item questionnaire. The results indicated that the overall enrollment of female students in STEM courses was relatively low, with significant variations across disciplines. The study identified personal interest, background knowledge, and academic success in

STEM-related subjects as key motivators for females to pursue STEM courses. Conversely, significant barriers were the lack of family and community support, lack of confidence in problem-solving, and the need for role models and mentors. The study recommends that universities and policymakers provide more resources and support to female students in STEM fields, such as mentorship programs, scholarships, and initiatives to promote gender equity.

In addition to these specific recommendations, there is a broader need for policy interventions that foster an environment conducive to innovation and creativity in STEM education. This includes establishing partnerships between educational institutions, industry, and government to provide students with practical, real-world experiences. Such collaborations can enhance the relevance of STEM education and better prepare students for the global job market demands. Furthermore, policies should encourage research and development in STEM fields, fostering a culture of inquiry and continuous learning.

The policy implications for STEM education in Africa are multifaceted and require a collaborative approach among various stakeholders. By focusing on teacher training, curriculum development, resource allocation, technology infrastructure, gender equity, and fostering innovation, African countries can significantly enhance the quality and impact of STEM education. These efforts will not only benefit students but also contribute to the broader socio-economic development of the continent.

5. Conclusion

This comprehensive study on STEM (Science, Technology, Engineering, and Mathematics) education in Africa has meticulously met its aim and objectives, providing an in-depth analysis of the multifaceted aspects of STEM education within the African context. The study successfully navigated through the historical evolution, current state, challenges, innovations, and the roles of various stakeholders in STEM education, aligning these elements with global trends and identifying critical gaps in the existing literature.

The study reveals a landscape marked by both challenges and opportunities. The historical analysis underscored the transition from traditional to modern educational frameworks, influenced significantly by external factors like colonialism. The current state of STEM education in Africa is characterized by resource limitations, gender disparities, and inadequate teacher training, which collectively impede the effectiveness of STEM education. However, the study also illuminated areas of innovation and technological integration, showcasing how digital technologies and active learning approaches are revolutionizing STEM education in Africa.

The role of government and non-governmental organizations emerged as pivotal in addressing the multifaceted challenges of STEM education. Collaborative efforts and international partnerships were identified as crucial for mobilizing resources and expertise. Comparative analysis with global trends highlighted that while Africa is embracing STEM education, there is a need for more targeted research and policy interventions to address its unique challenges and opportunities.

In conclusion, this study recommends a multi-pronged approach to enhance STEM education in Africa. This includes policy reforms focused on improving teacher training, updating curricula, enhancing resource allocation, and promoting gender equity. Additionally, leveraging technological innovations and fostering international collaborations can significantly contribute to the advancement of STEM education. By addressing these key areas, STEM education in Africa can be transformed, empowering students and contributing to the continent's sustainable development. This study serves as a foundational reference for policymakers, educators, and international organizations working towards the enhancement of STEM education in Africa.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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