

ENGINEERING FOR SUSTAINABLE DEVELOPMENT IN AFRICA: CHALLENGES, INNOVATIONS, AND COLLABORATIVE PATHWAYS

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Abstract: This research article explores the unique challenges and opportunities present in the field of engineering in Africa, motivated by the continent's rapid development and the critical need for sustainable solutions. Despite abundant resources and a youthful population, Africa faces significant obstacles, including inadequate infrastructure, limited access to education, and socio-economic disparities. The study analyzes various engineering disciplines, highlighting innovations that address local issues, such as renewable energy technologies, water management systems, and transportation networks. Key findings indicate that collaborative efforts among governments, academia, and industry stakeholders are essential for fostering an environment conducive to engineering advancements. Additionally, the research identifies a growing emphasis on local content in engineering projects, which not only promotes economic growth but also enhances skills transfer and capacity building within communities. The implications of this study are far-reaching, suggesting that by investing in engineering education and infrastructure, African nations can harness their potential, drive technological innovation, and improve the quality of life for their citizens. This article aims to contribute to a greater understanding of the engineering landscape in Africa and inspire further research and investment in the region, ultimately leading to sustainable development and prosperity.

Keywords: Engineering; Research; Africa; Sustainable development and prosperity

1 INTRODUCTION

Engineering research in Africa is a critical field that holds the potential to address numerous local challenges while simultaneously driving economic development and fostering innovation. With diverse and complex problems ranging from inadequate infrastructure to energy shortages, the necessity for targeted engineering solutions is more pressing than ever. As the continent grapples with rapid urbanization and climate change, engineering research emerges as a vital element in crafting sustainable responses tailored to the unique context of African nations.

The current state of engineering education and research across various African countries reveals a mixed landscape. While some nations, such as South Africa and Kenya, have made significant strides in establishing robust engineering programs and research initiatives, others still face substantial hurdles. Challenges include limited funding, inadequate facilities, and a shortage of qualified educators, which hinder the development of a capable workforce. Despite these obstacles, there is a palpable enthusiasm among students and young professionals, driven by a desire to innovate and contribute to their communities.

In recent years, there has been a growing recognition of the importance of local content in engineering projects. This shift not only aims to enhance project outcomes but also focuses on building local capacity through skills transfer and knowledge sharing. Collaborative efforts between governments, universities, and industry stakeholders have become increasingly necessary to create an ecosystem that nurtures engineering talent and encourages research that addresses the continent's pressing needs.

Ultimately, engineering research in Africa stands at a crossroads where it can significantly impact the continent's future. By investing in education and fostering a culture of innovation, African nations can leverage engineering as a catalyst for growth and development, ensuring that local challenges are met with sustainable and effective solutions.

2 HISTORICAL CONTEXT OF ENGINEERING IN AFRICA

The historical evolution of engineering practices in Africa is a tapestry woven from indigenous knowledge, colonial influences, and post-colonial developments. Indigenous engineering methods have existed for centuries, as communities utilized local materials and traditional techniques to construct structures, manage water resources, and create agricultural systems. Notable examples include the ancient pyramids of Egypt, the intricate irrigation systems of the Shona people in present-day Zimbabwe, and the stone houses of the Zulu in South Africa. These practices showcased a deep understanding of the environment and sustainable resource management.

However, the colonial era profoundly altered the engineering landscape. European powers imposed their own engineering standards and practices, often disregarding indigenous techniques. Infrastructure projects such as railways and roads were constructed primarily to facilitate resource extraction and control territories, rather than to benefit local communities. This period also saw the introduction of formal engineering education in Africa, with institutions established by colonial powers aiming to train a small elite rather than fostering broad access to engineering knowledge.

The post-colonial period marked a significant turning point in engineering practices across the continent. Newly independent nations prioritized the need to develop local engineering capacity, leading to the establishment of various engineering institutions. For instance, the University of Nairobi in Kenya and the University of Cape Town in South Africa emerged as key players in engineering education, promoting research that aligned with local needs. Additionally, many African countries began to embrace local content in engineering projects, emphasizing the importance of homegrown solutions and skills transfer.

Noteworthy milestones in engineering education include the formation of the African Engineering Education Association in the early 2000s, which aimed to enhance the quality of engineering programs across the continent. Today, engineering practices in Africa continue to evolve, driven by a blend of indigenous knowledge, modern techniques, and a commitment to addressing the continent's unique challenges.

2.1 Current Trends in Engineering Research

The landscape of engineering research in Africa is witnessing a transformative shift, characterized by a growing focus on renewable energy technologies, sustainable infrastructure, and technology-driven solutions. As nations grapple with the realities of climate change and energy shortages, innovative approaches that harness local resources and expertise are becoming paramount. Countries are increasingly investing in solar, wind, and biomass energy as viable alternatives to traditional fossil fuels, with research institutions leading the charge in developing and implementing these technologies.

Sustainable infrastructure is another area garnering attention in engineering research. The need for resilient urban centers that can withstand environmental stresses has prompted engineers to explore eco-friendly building materials, waste management systems, and efficient transportation networks. For instance, the integration of green building practices and smart city technologies is being researched to enhance urban living while minimizing environmental impacts. These projects often prioritize local materials and labor, ensuring that communities benefit directly from the advancements.

Partnerships between universities and industries are playing a crucial role in driving these trends forward. Collaborative initiatives are emerging, where academic research is aligned with industry needs, fostering a culture of innovation that addresses real-world problems. For example, universities are partnering with local governments and businesses to develop renewable energy projects that not only provide power but also create jobs and stimulate local economies. Such synergies are essential for translating research into practical applications that can improve the quality of life for citizens.

Moreover, technology-driven solutions are being embraced across various sectors, including agriculture, healthcare, and telecommunications. The rise of digital platforms and mobile technologies is facilitating access to information and services, thereby enhancing productivity and efficiency. Research focused on integrating these technologies into engineering practices is crucial for ensuring that Africa does not lag in the global technological landscape.

In summary, the current trends in engineering research within Africa reflect a proactive approach to tackling pressing issues through innovation and collaboration. With a strong emphasis on sustainable practices and local partnerships, the continent is poised to make significant strides in engineering advancements that can lead to long-term development and prosperity.

2.2 Challenges Faced by Engineers in Africa

Engineers in Africa encounter a myriad of challenges that significantly hinder their ability to implement effective solutions to local problems. One of the foremost issues is the lack of funding for engineering projects. According to the African Development Bank, the continent requires approximately \$170 billion annually to address its infrastructure deficits, yet only a fraction of this amount is available. This funding gap severely limits the capacity for large-scale projects and innovations that could transform communities.

Inadequate infrastructure is another pressing concern. Many regions lack essential services such as reliable electricity, clean water, and efficient transportation systems. This deficiency not only hampers engineering efforts but also affects the overall economic development of countries. A case study from Nigeria illustrates this challenge: over 40% of the population lacks reliable access to electricity, which stifles industrial growth and innovation.

Brain drain exacerbates the situation, as skilled engineers often migrate to developed countries in search of better opportunities and working conditions. The World Bank estimates that up to 30% of highly educated professionals from sub-Saharan Africa have relocated abroad. This exodus creates a significant shortage of qualified engineers who can address local challenges and implement sustainable solutions.

Moreover, limited access to advanced technology poses a considerable barrier. Many African engineers lack exposure to cutting-edge tools, software, and methodologies that are essential for modern engineering practices. For instance, while

countries like South Africa and Kenya are making strides in technology adoption, other nations lag behind due to insufficient investment in research and development.

The combination of these challenges creates a complex landscape for engineers in Africa. Tackling these issues requires a concerted effort from governments, educational institutions, and private sectors to invest in infrastructure, attract and retain talent, and provide access to modern technologies. By addressing these critical areas, Africa can unlock the potential of its engineering workforce and drive sustainable development across the continent.

2.3 Case Studies of Successful Engineering Projects

Across Africa, numerous engineering projects have emerged as beacons of success, demonstrating innovative approaches to local challenges while yielding significant community impacts. This section highlights several case studies that exemplify the power of engineering in driving sustainable development.

One notable project is the Kakuma Refugee Camp Solar Microgrid in Kenya. The objective of this initiative was to provide reliable and sustainable energy to the camp, which hosts over 190,000 refugees. Implemented by a consortium of NGOs and energy companies, the methodology involved the installation of solar panels and battery storage systems. The outcome was not only a reduction in reliance on diesel generators but also a significant decrease in energy costs for residents. The microgrid has empowered local businesses, facilitated educational programs, and improved healthcare services, showcasing the potential for renewable energy to transform lives in challenging environments.

In South Africa, the Zola Electrification Project serves as another compelling case study. Launched to address the energy needs of underprivileged communities, the project aimed to electrify informal settlements in the Zola area of Soweto. By employing a community-driven approach, local residents were involved in the planning and implementation phases. This not only ensured that the solutions were tailored to their specific needs but also fostered a sense of ownership. As a result, the project successfully connected thousands of households to the national grid, enhancing safety, education, and economic opportunities in the community [1].

The Water and Sanitation Project in Addis Ababa, Ethiopia, also stands out as a model of engineering success. Faced with a growing urban population and inadequate infrastructure, this project sought to improve access to clean water and sanitation facilities. Utilizing a participatory approach, engineers collaborated with local communities to design and construct water supply systems and sanitation facilities. The outcomes were profound, leading to a significant reduction in waterborne diseases and improved overall health in the community. The project not only addressed immediate needs but also promoted sustainable water management practices that will benefit future generations.

Each of these case studies underscores the pivotal role of engineering in fostering sustainable development across Africa. By employing innovative methodologies and engaging local communities, these projects have demonstrated the potential for engineering solutions to create lasting positive impacts.

3 THE ROLE OF GOVERNMENT AND POLICY IN ENGINEERING

Government policies play a pivotal role in shaping the landscape of engineering research and development. They can either facilitate progress and innovation or hinder it through bureaucratic hurdles and lack of support. In many African countries, the government's commitment to engineering and technology development is reflected in various initiatives aimed at enhancing the sector's capabilities. For instance, investment in educational programs, research grants, and public-private partnerships are critical strategies employed to foster engineering talent and infrastructure.

One significant initiative is the establishment of national engineering councils and regulatory bodies that set standards for engineering practices and education. These organizations often collaborate with universities to ensure that curricula align with industry needs, thereby improving the employability of graduates. Furthermore, governments can incentivize research and development through tax breaks and grants for companies that invest in innovative engineering solutions. This approach not only stimulates local research but also encourages foreign investment, as companies seek to capitalize on the burgeoning engineering sector.

However, many African nations still grapple with policies that inhibit engineering growth. Challenges such as cumbersome regulatory processes, insufficient funding for research institutions, and a lack of infrastructure investment can stifle innovation. For example, engineers often face delays in project approvals due to bureaucratic inefficiencies, which can lead to increased costs and project abandonment. Inadequate funding for engineering education and research also results in a shortage of skilled professionals, further exacerbating the challenges faced by the sector.

Noteworthy examples of successful government initiatives include the African Union's Agenda 2063, which emphasizes the importance of science, technology, and innovation in driving sustainable development. Additionally, various countries have implemented policies aimed at enhancing STEM (Science, Technology, Engineering, and Mathematics) education at all levels, recognizing that a strong foundation in these fields is essential for future engineering advancements.

In summary, the interplay between government policy and engineering development is complex and multifaceted. Effective policies can serve as catalysts for growth, while inadequate or poorly implemented regulations can impede progress. By

prioritizing engineering through supportive policies and investment, governments can significantly enhance the capacity and capability of the engineering sector, ultimately contributing to the continent's development goals.

3.1 Indigenous Knowledge and Technology Integration

The integration of indigenous knowledge systems with modern engineering practices is increasingly recognized as a vital approach to developing sustainable solutions that resonate with local communities. Indigenous knowledge, deeply rooted in cultural traditions and environmental stewardship, offers valuable insights that can enhance contemporary engineering methodologies. By merging these two distinct yet complementary knowledge systems, engineers can create solutions that are not only technically sound but also culturally relevant and ecologically sustainable.

One prominent example of successful integration is the Mokoro Project in Botswana, which focuses on sustainable water management in the Okavango Delta. Local communities possess extensive knowledge about the hydrology of the delta, traditionally using their understanding of seasonal changes and indigenous plant species to manage water resources. Engineers working alongside these communities have combined this traditional expertise with modern hydrological modeling techniques to develop a comprehensive water management plan. This collaboration has resulted in improved water conservation practices that respect local customs while addressing the challenges posed by climate change [2].

Another noteworthy case is the Indigenous Forestry and Engineering Collaboration in Canada, where traditional ecological knowledge has been integrated into forest management practices. Indigenous communities have long employed sustainable methods of resource extraction that consider biodiversity and ecosystem health. By partnering with engineers and environmental scientists, these communities have developed innovative timber harvesting practices that reduce environmental impact while enhancing economic opportunities. This synergy not only protects the forest ecosystem but also revitalizes indigenous economies, demonstrating a successful model for integrating traditional knowledge with modern engineering.

In the realm of renewable energy, the Sustainable Energy for All (SE4ALL) initiative showcases how indigenous knowledge can play a crucial role in the deployment of solar energy solutions. In various regions of Africa, local populations have utilized their understanding of sun patterns and resource availability to design solar energy systems that are tailored to their specific needs. Engineers collaborating with these communities have been able to create more efficient energy solutions that align with cultural practices and local preferences, ultimately leading to increased adoption and satisfaction.

These examples illustrate the importance of integrating indigenous knowledge systems with contemporary engineering practices. Such collaborations not only yield innovative solutions but also empower local communities, fostering a sense of ownership and stewardship over their resources. By valuing and incorporating indigenous knowledge, the engineering field can enhance its relevance and effectiveness in addressing the unique challenges faced by diverse populations across Africa and beyond.

3.2 Future Prospects for Engineering Research

The future of engineering research in Africa is poised for significant transformation, particularly with the advent of emerging technologies such as artificial intelligence (AI), robotics, and bioengineering. As these technologies evolve, they present unique opportunities for addressing the continent's pressing challenges, ranging from healthcare accessibility to infrastructure development and environmental sustainability.

Artificial intelligence is set to revolutionize various sectors in Africa. From predictive analytics in agriculture that can enhance crop yields to AI-driven healthcare applications improving diagnostics and patient care, the potential is immense. Governments and research institutions are increasingly investing in AI training programs, creating a workforce capable of harnessing this technology. Moreover, AI can facilitate data-driven decision-making in urban planning, resource management, and disaster response, making it a crucial tool for sustainable development.

Robotics also holds promise for engineering research in Africa, particularly in sectors where labor shortages exist. Automated systems can optimize manufacturing processes and improve productivity across industries, such as mining and agriculture. Emerging initiatives, like robotics competitions in schools, are fostering interest in this field among young engineers. Collaborations with international partners can further enhance research in robotics, providing access to advanced technologies and expertise [3].

Bioengineering is another frontier with vast potential. With Africa's rich biodiversity, bioengineering research can lead to innovative solutions tailored to local needs, such as developing drought-resistant crops or affordable medical devices. The continent's unique ecosystems offer a wealth of biological resources that can be harnessed for sustainable practices, contributing to global efforts in combating climate change and promoting health equity.

International collaboration will be pivotal in advancing engineering research in Africa. Partnerships with universities and research institutions worldwide can facilitate knowledge exchange, technology transfer, and funding opportunities. Collaborative projects can address shared challenges, such as climate change adaptation, and leverage diverse expertise to

create innovative solutions. By fostering a culture of collaboration, Africa can position itself as a leader in engineering research, driving sustainable development and enhancing its global competitiveness.

3.3 Comparative Analysis with Other Regions

The comparative analysis of engineering research capacity in Africa versus regions such as Europe and Asia reveals significant disparities in performance metrics such as publications, funding, and research output. While Africa is experiencing a gradual increase in research activity, particularly in sectors like renewable energy and sustainable development, it still lags behind more established regions.

In Europe, engineering research is characterized by robust funding mechanisms and a high volume of publications. The European Union invests heavily in research and innovation through programs like Horizon Europe, which allocates billions of euros to foster technological advancements and collaborations. This investment results in a wealth of high-impact publications, with European countries leading in various engineering disciplines, including civil, mechanical, and environmental engineering. The emphasis on interdisciplinary research and international collaboration further amplifies the research output in Europe.

In contrast, Africa faces challenges related to limited funding for research initiatives. Many African nations allocate only a small percentage of their GDP to research and development, which impacts the capacity of local universities and research institutions to produce high-quality engineering research. Despite the enthusiasm of young engineers and researchers, the lack of adequate resources often hampers their ability to publish findings in reputable journals or to participate in global research networks [4].

Asia presents an intriguing case, with countries like China and India rapidly advancing their engineering research capabilities. China, in particular, has made substantial investments in infrastructure and technology, leading to a significant increase in research output and publications. The country's focus on innovation and technology transfer has positioned it as a global leader in engineering, surpassing many Western nations in various metrics. India, with its growing technology sector, is also seeing an increase in engineering research, particularly in software and telecommunications.

While Africa is beginning to harness local knowledge and cultivate partnerships between academia, industry, and government, it remains essential to address the funding gaps and infrastructure deficits that limit research capacity. By learning from the successful frameworks established in Europe and Asia, African nations can develop targeted strategies to enhance their engineering research landscape, ultimately contributing to sustainable development and economic growth.

3.4 Education and Capacity Building

Education plays a pivotal role in developing a skilled engineering workforce in Africa, which is essential for addressing the continent's unique challenges and harnessing its vast potential. To cultivate an effective engineering workforce, it is crucial to not only enhance the quality of engineering curricula but also foster research skill development among students. A robust educational framework can empower future engineers to innovate and implement sustainable solutions that directly benefit their communities [5].

One of the primary recommendations for strengthening engineering curricula is the integration of practical, hands-on learning experiences. Curricula should be designed to include project-based learning, internships, and collaborations with local industries. This approach not only equips students with theoretical knowledge but also provides them with practical skills and real-world exposure necessary for their professional growth. By engaging with local engineering challenges, students can apply their learning in meaningful ways, fostering a sense of ownership and responsibility towards their communities.

Furthermore, curricula should emphasize interdisciplinary learning, combining engineering principles with subjects such as environmental science, economics, and social studies. This holistic approach can help future engineers develop a broader perspective on the implications of their work and encourage innovative solutions that address socio-economic and environmental issues. Institutions should also focus on incorporating emerging technologies, such as artificial intelligence and renewable energy systems, into their programs to ensure that students are well-versed in the latest advancements [6].

In addition to curriculum development, fostering research skill development is vital. Universities should provide opportunities for undergraduate and graduate students to engage in research projects, ideally in collaboration with faculty members and industry partners. By encouraging students to participate in research, institutions can nurture critical thinking, problem-solving skills, and creativity. This not only enhances the students' educational experience but also contributes to the advancement of engineering knowledge in Africa.

Ultimately, investing in education and capacity building is essential for cultivating a skilled engineering workforce capable of driving sustainable development across the continent. By enhancing engineering curricula and fostering research skill development, African nations can empower their youth to become innovative leaders who can effectively tackle local challenges.

3.5 Role of International Collaboration

International collaboration plays a crucial role in advancing engineering research in Africa, significantly enhancing research capacity and fostering innovation. Through partnerships with universities, research institutions, and industries around the globe, African nations can leverage external expertise, funding, and technology, which are often scarce locally. Such collaborations are particularly essential in addressing complex engineering challenges, including infrastructure development, renewable energy adoption, and sustainable resource management.

One notable example of successful international collaboration is the African Research Universities Alliance (ARUA), which brings together top research universities across Africa to collaborate on addressing the continent's pressing challenges. ARUA has established partnerships with leading global institutions, facilitating joint research projects and capacity-building initiatives. Through these partnerships, African researchers gain access to cutting-edge research facilities and resources, fostering an environment conducive to innovative engineering solutions [7].

Another impactful program is the Engineering for Development (E4D) initiative, which focuses on enhancing engineering education and research capacity in developing countries, including several African nations. By partnering with universities in Europe and North America, E4D provides training, funding, and resources to support engineering projects that directly address local needs. This initiative has successfully contributed to building a skilled workforce capable of implementing sustainable engineering solutions in various sectors, such as water management and renewable energy.

Furthermore, international collaborations often lead to knowledge exchange and skills transfer, empowering local engineers and researchers. Programs such as the Global Innovation through Science and Technology (GIST), supported by the U.S. Department of State, encourage collaboration between American and African innovators. GIST fosters entrepreneurship and technological innovation, enhancing the capacity of local teams to develop solutions tailored to regional challenges.

In summary, international collaboration is vital for advancing engineering research in Africa. By fostering partnerships that leverage global expertise and resources, African nations can enhance their research capacity, drive technological innovation, and ultimately contribute to sustainable development across the continent [8].

4 ETHICS AND SUSTAINABILITY IN ENGINEERING

In the context of engineering practice in Africa, ethical considerations and sustainability issues are increasingly central to decision-making processes. As the continent faces unique socio-economic challenges, engineers must navigate a complex landscape that includes resource scarcity, environmental degradation, and the need for inclusive development. The ethical dimension of engineering encompasses accountability to local communities, respect for cultural values, and the pursuit of equitable solutions that foster long-term sustainability [9].

One significant ethical consideration is the impact of engineering projects on the environment and local communities. Engineers are tasked with designing solutions that not only address immediate needs but also consider the long-term consequences of their actions. For instance, infrastructure projects must evaluate potential environmental impacts, such as habitat destruction or water pollution, and strive to incorporate sustainable practices that mitigate these effects. It is crucial for engineers to embrace a holistic approach that prioritizes ecological integrity while delivering essential services.

Frameworks for ensuring responsible engineering decisions include adherence to established ethical guidelines and standards. Organizations such as the International Federation of Consulting Engineers (FIDIC) and the American Society of Civil Engineers (ASCE) provide codes of ethics that emphasize integrity, transparency, and social responsibility. Additionally, the integration of sustainability principles into engineering education equips future professionals with the knowledge to make informed decisions that align with ethical standards.

Moreover, stakeholder engagement is vital in the engineering process, allowing for diverse perspectives to inform project planning and execution. By actively involving local communities in decision-making, engineers can better understand the specific needs and concerns of those affected by their work, fostering trust and promoting ethical accountability.

To promote sustainability, engineers should also consider the lifecycle of projects, emphasizing renewable resources, energy efficiency, and waste reduction. The implementation of sustainable engineering practices not only addresses urgent infrastructure needs but also contributes to the broader goal of sustainable development, ensuring that future generations can thrive within a balanced ecological framework [10].

5 CONCLUSION

In summary, this paper has explored the critical role that engineering research plays in driving Africa's growth and development. Through various sections, we have highlighted the unique challenges faced by the continent, including inadequate infrastructure, limited access to education, and socio-economic disparities. Despite these hurdles, engineering research holds immense potential to create innovative solutions tailored to local contexts, fostering sustainable progress.

We've seen that a collaborative approach among governments, academia, and industry stakeholders is essential for cultivating an environment conducive to engineering advancements. Emphasizing local content in engineering projects not only stimulates economic growth but also promotes skills transfer, capacity building, and community empowerment. The historical context of engineering in Africa reveals a legacy of both indigenous practices and colonial influences, which continue to shape the current landscape and inform future initiatives.

Current trends reflect a shift towards sustainable energy solutions, eco-friendly infrastructure, and technology-driven approaches, showcasing a proactive response to pressing issues such as climate change and urbanization. However, challenges such as funding limitations and the need for enhanced educational frameworks must be addressed to unlock the full potential of engineering research.

As we look to the future, the landscape of engineering in Africa is poised for transformation. By investing in education, fostering international collaborations, and adhering to ethical and sustainable practices, the continent can harness its engineering capabilities to drive meaningful development. The journey ahead presents a unique opportunity for African nations to emerge as leaders in engineering innovation, ultimately improving the quality of life for their citizens and contributing to global advancements [11].

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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