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Internet-Based Experiments for EEE Education in Sudan: Opportunities and Roadmap

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ABSTRACT

This paper examines the role of internet-based technologies in rebuilding, modernizing, and sustaining electrical and electronic engineering (EEE) education in Sudan. Amid infrastructure collapse and limited resources, virtual, remote, and hybrid laboratories offer practical alternatives to traditional lab environments. The study reviews global case studies and presents a phased implementation strategy suited to Sudanese universities—beginning with virtual simulations, expanding to kit-based hybrid labs, and culminating in shared remote lab networks. A SWOT analysis identifies key enablers and risks. While challenges such as internet access and faculty training persist, online labs represent a strategic opportunity to restore and future-proof EEE education in post-conflict settings.

1. INTRODUCTION

Laboratory-based education forms an integral part of engineering curricula across the globe. In electrical and electronic engineering, in particular, laboratory sessions are essential for transforming theoretical knowledge into practical understanding. These sessions allow students to explore circuit behavior, test theoretical predictions, validate simulation results, and develop hands-on skills in designing, assembling, and troubleshooting electrical systems. Through laboratory experiences, students also build competencies in teamwork, experimental design, measurement techniques, data analysis, and report writing—all of which are fundamental to professional engineering practice [1], [2].

Traditionally, such laboratories are conducted in dedicated physical spaces equipped with specialized hardware like oscilloscopes, signal generators, power supplies, and prototyping boards. However, maintaining and updating these facilities demands significant financial and logistical resources. Moreover, their effectiveness depends on continuous access, trained personnel, and safe learning environments—conditions not always guaranteed in regions affected by conflict, economic hardship, or natural disasters [3].

The recent conflict in Sudan and the COVID-19 pandemic further exposed the vulnerabilities of purely physical lab infrastructures. Many institutions were forced to suspend in-person activities, leading to the accelerated development and adoption of online laboratory alternatives [4]. This global shift demonstrated that virtual and remote laboratories are not just contingency solutions but valuable pedagogical tools that can complement and even enhance traditional lab learning [5].

In the context of Sudan and similar countries facing infrastructural challenges, the integration of internet-based laboratory solutions presents an opportunity to democratize engineering education. By leveraging affordable digital platforms, educators can provide students with meaningful experimental experiences regardless of their geographical or economic circumstances. This paper aims to explore the feasibility of using internet technologies to conduct local experiments for electrical and electronic engineering students. It highlights global best practices, categorizes available tools, evaluates pedagogical impacts, and proposes a roadmap for adopting such technologies in the Sudanese educational context and beyond.

2. ELECTRICAL AND ELECTRONICS ENGINEERING (EEE) EDUCATION IN SUDAN

Electrical and Electronics Engineering (EEE) education in Sudan has played a pivotal role in the country's technical and industrial development, with major institutions such as the University of Khartoum and Sudan University of Science and Technology leading the field. According to the Ministry of Higher Education and Scientific Research, as of 2022, over 7,000 students were enrolled in EEE-related programs across more than 15 public and private universities in Sudan [6].

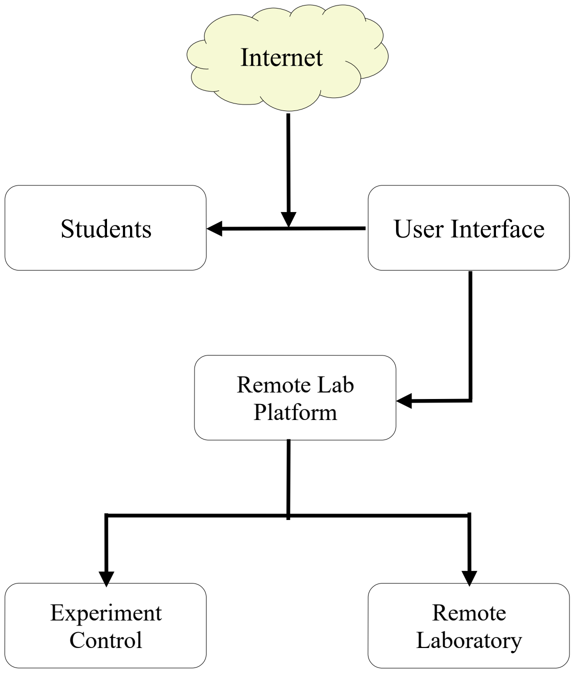

Figure 1: Overview diagram of the remote laboratory setup

The University of Khartoum alone graduates approximately 100 engineers annually from its Department of Electrical and Electronic Engineering, with specialization tracks in power systems, communications, and control engineering [7]. However, the sector faces numerous challenges, including outdated laboratory infrastructure, limited access to modern simulation tools, and a high rate of skilled migration, with estimates suggesting that over 40% of engineering graduates seek employment or postgraduate opportunities abroad [8]. Furthermore, national research output in the field remains modest, with EEE-related publications accounting for less than 5% of Sudan's total scientific publications in Scopus-indexed journals between 2018 and 2022 [9].

Despite these constraints, there is a growing interest in aligning EEE education with emerging fields such as digital transformation, renewable energy, and digital technologies, particularly due to the increasing demand for sustainable power solutions and the post-conflict reconstruction of critical infrastructure [10].

3. CURRENT STATE OF ELECTRICAL AND ELECTRONICS ENGINEERING LABORATORIES IN SUDANESE UNIVERSITIES

The armed conflict that erupted in Sudan in April 2023 has had a profound impact on higher education infrastructure, including electrical and electronics engineering laboratories. Prior to the conflict, Sudanese universities such as the University of Khartoum, Sudan University of Science and Technology (SUST), and the University of Medical Sciences and Technology (UMST) had made significant investments in upgrading laboratory facilities to meet international standards [11]. These facilities supported hands-on training in areas such as electrical machines, power systems, automation, electronics, and control systems.

However, the war has disrupted educational services, damaged infrastructure, and displaced academic staff and students. Many universities in Khartoum and other conflict-affected areas have faced looting, vandalism, or complete shutdowns [12]. As a result, the operational status of many laboratories is uncertain. Institutions that once housed advanced training systems—such as the Lucas-Nülle-supported labs at the University of Khartoum—now struggle to maintain functionality due to limited access, lack of maintenance, and loss of funding [13].

Universities that relocated to relatively stable areas like Port Sudan or resumed partial online instruction face challenges in replicating laboratory experiences remotely. There is a significant risk that the lack of hands-on training will widen the gap between Sudanese graduates and global engineering competencies [14]. Furthermore, the interruption in research and industry collaboration undermines Sudan's capacity to develop local engineering solutions.

Despite the grim outlook, there are signs of resilience. Faculty members and university administrators are exploring alternative solutions such as partnerships with international organizations, remote simulation tools, and decentralized lab models [15]. Many institutions in safer areas have resumed limited activity, though they face significant resource limitations.

This critical situation is expected to continue even after the cessation of hostilities. The destruction of infrastructure, displacement of academic personnel, and economic collapse will likely hinder immediate recovery. Rebuilding engineering laboratories requires long-term investment, international support, and a stable political environment—conditions that may take years to materialize [16].

In sum, the war has severely compromised the capacity of Sudanese universities to deliver practical engineering education. A concerted national and international effort is required to restore and rebuild these critical facilities as part of a broader strategy for post-conflict educational recovery and development.

4. GLOBAL RECOVERY MODELS AND WHAT SUDAN CAN LEARN

Countries recovering from conflict or facing systemic educational disruptions have increasingly turned to online and remote laboratories as strategic solutions to rebuild engineering education. While the political and economic contexts may differ, these cases offer valuable lessons that can inform Sudan's own post-conflict strategy (see Appendix A for implementation roadmap and cost estimates).

4.1. Post-Conflict Recovery: Lessons for Sudan's War-Affected Universities

1. Iraq (Post-2003 Conflict)

Iraqi universities, particularly in Baghdad and Mosul, experienced severe destruction of laboratory infrastructure after the 2003 invasion. Recovery strategies included partnerships with organizations like UNESCO and USAID, deployment of mobile labs and simulations, and engagement of diaspora professionals to support faculty development [17].

Relevance to Sudan: Sudanese universities facing displacement and lab destruction—particularly in Khartoum—can emulate this model by engaging the Sudanese academic diaspora and collaborating with UNESCO or Education Cannot Wait (ECW) to set up mobile lab solutions in safer regions like Port Sudan.

2. Syria (Post-2011 Civil War)

Syria's civil war displaced students and damaged university campuses. Responses included the establishment of branches in safer cities, implementation of virtual labs through NGO partnerships, and a focus on restoring basic lab functionality before research facilities [18].

Relevance to Sudan: Sudan's relocation of educational activities to cities like Gedaref and Kassala mirrors Syria's decentralization strategy. Virtual labs can serve as an essential stopgap for maintaining engineering instruction amid physical lab losses.

3. Rwanda (Post-1994 Genocide)

Rwanda's post-genocide recovery included major reforms in technical education, creation of TVET centers, alignment of curricula with national development priorities, and strong donor engagement (e.g., DFID, GIZ) [19].

Relevance to Sudan: Sudan can align its EEE lab recovery strategy with national reconstruction goals in energy and ICT. Strong policy direction and donor alignment—similar to Rwanda's model—could accelerate the rebuilding process.

4. Liberia and Sierra Leone (Post-Civil Wars)

Post-conflict education in Liberia and Sierra Leone was supported through the donation of refurbished equipment, regional academic cooperation, and inclusion of civic education in technical training [21].

Relevance to Sudan: Sudan could pursue South–South academic partnerships with institutions in Africa and the Arab region to access equipment and capacity-building support. This reduces dependency on high-cost imports.

4.2. Scalable Models of Online Laboratories

1. Europe: Shared Remote Labs

Programs such as VISIR and WebLab-Deusto, funded under the EU's Horizon 2020 framework, enable interoperable remote labs shared across institutions [5].

Relevance to Sudan: Sudanese universities could establish a national network of shared remote labs using a similar model, reducing duplication and extending access to students across public institutions (see Appendix A, Phase 3).

2. United States: MOOC-Integrated Engineering Labs

Institutions like MIT and Stanford have developed platforms (e.g., MIT iLabs, Labster) that combine interactive labs with MOOCs, enabling remote and blended learning [23].

Relevance to Sudan: By combining open online courses with locally developed lab content, Sudanese institutions can expand learning opportunities without starting from scratch.

3. India: Government-Funded Virtual Labs

India's Virtual Labs initiative delivers free, curriculum-aligned simulations in local languages, accessible even on low-bandwidth internet [22].

Relevance to Sudan: Sudan can replicate this model with Arabic-language virtual labs accessible via mobile devices, enabling students in rural areas to engage in EEE experiments (see Appendix A, Phase 1).

4. Africa: Emerging Hybrid Lab Initiatives

Universities in South Africa, Kenya, and Ghana have piloted Arduino-based kits and cloud platforms to support hybrid learning, often in collaboration with NGOs [23].

Relevance to Sudan: These low-cost kits are ideal for Sudanese students who can assemble them at home, especially in areas where institutions lack physical labs (see Appendix A, Phase 2).

4.3. Summary of Global Insights and Sudanese Applications

Country	Strategy Used	Relevance to Sudan
Iraq	Mobile labs, diaspora engagement	Engage diaspora and use mobile kits in Port Sudan
Syria	Virtual labs in relocated campuses	Use virtual labs in Gedaref and Kassala
Rwanda	Curriculum aligned with national goals	Align lab rebuilding with energy and ICT priorities
Liberia/ Sierra Leone	Donated equipment, regional collaboration	Pursue South–South partnerships for lab resources
India	Free, localized virtual labs	Build Arabic simulations for low-bandwidth users
Europe	Shared online lab networks	Create a national shared lab platform
US (MIT, Stanford)	MOOC + Remote lab integration	Localize MOOC-linked labs for Sudanese curricula
Kenya/Ghana	Hybrid kits and dashboards	Distribute Arduino kits for remote learning

These global experiences not only offer technical solutions but also policy frameworks, funding mechanisms, and curriculum strategies. Sudan can selectively adapt and combine them to create a resilient, inclusive, and forward-looking engineering education system (see Section 13 of the full paper for national context and Appendix A for implementation models).

5. EEE LABORATORY SYSTEM ARCHITECTURE

The proposed remote and hybrid laboratory system is architected to deliver flexible, scalable, and interactive access to experimental resources for electrical and electronic engineering (EEE) students. It incorporates a modular design that integrates real-time control, remote interfacing, and optional simulation technologies, ensuring that practical learning continues even in disrupted or resource-constrained environments.

The core components of the architecture include:

1. Remote User Interface

Students interact with the laboratory system through a secure web-based portal or an AR/VR-enabled interface. This interface allows them to monitor equipment status, issue commands, visualize experiment progress, and receive real-time data and feedback.

2. Communication Layer

This middleware ensures seamless and secure data exchange between users and hardware. It relies on standard internet protocols, authentication services, and low-latency communication techniques to maintain responsiveness during live experiments.

3. Lab Control Server

Serving as the system's central node, the control server receives user inputs, processes requests, and interfaces with physical devices. It also handles experiment queuing, scheduling, user authentication, and data logging.

4. Physical Laboratory Equipment

The lab includes real hardware such as oscilloscopes, sensors, embedded systems, electrical machines, and power electronics devices. These are interfaced with the control server via programmable logic controllers (PLCs) or microcontrollers like Arduino or Raspberry Pi [24].

5. Simulation and AR/VR Modules (Optional)

To improve interactivity and ensure continuity when physical equipment is unavailable, the architecture incorporates simulation tools and AR/VR environments. These modules mirror the real lab configuration, allowing students to gain familiarity with setups and processes before physical engagement.

6. AI-Based Monitoring and Feedback (Optional)

An optional AI layer monitors user activity, assesses performance, and provides real-time feedback. It can deliver personalized guidance, adaptive learning paths, and remedial content to support differentiated instruction.

Figure 2 illustrates the hybrid laboratory architecture, showing the interaction between students, user interfaces, control systems, and both real and virtual lab elements.

6. TYPES OF ONLINE LABORATORIES

Online laboratories for electrical and electronic engineering (EEE) education are typically classified into three categories: **virtual laboratories**, **remote laboratories**, and **augmented or hybrid laboratories**. Each type has distinct pedagogical value depending on the educational level, resource availability, and instructional goals.

5.1. Virtual Laboratories (Simulated Labs)

Virtual labs are software-based simulations that mimic real-world electronic systems and experiments. These are ideal for introductory or theory-heavy courses where physical experimentation is not essential.

- **Features**: Graphical interfaces, real-time simulations, modifiable parameters, and embedded assessments.
- **Advantages**: Low-cost, highly scalable, and accessible via standard web browsers.
- **Limitations**: Lack of physical interaction and real-world variability.

Example: *Tinkercad Circuits* by Autodesk is a free, browser-based tool where students can design and simulate electronic circuits and program microcontrollers like Arduino [25].

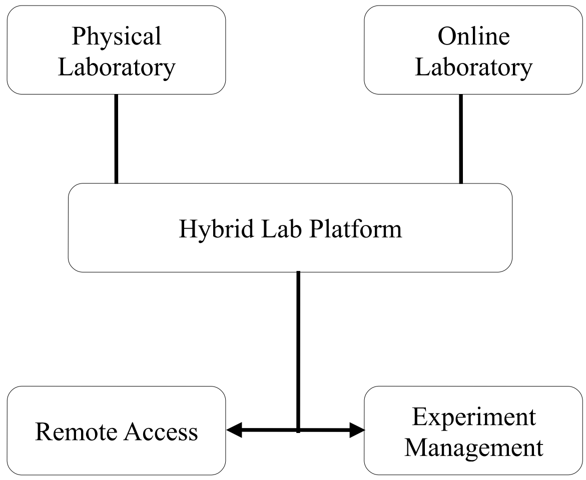

Figure 2: Hybrid Laboratory Architecture

5.2. Remote Laboratories

Remote labs provide internet-based access to real lab hardware, allowing students to conduct physical experiments from a distance. These labs are especially useful for intermediate to advanced courses.

- **Features**: Real-time control of equipment, video monitoring, and data acquisition systems.
- **Advantages**: High fidelity, authentic lab experience, access to professional-grade instruments.
- **Limitations**: Requires significant backend infrastructure and scheduled access to hardware.

Example: *MIT iLabs* enables students at partner institutions worldwide to access physical lab instruments such as oscilloscopes and signal generators over the web [5].

5.3. Augmented or Hybrid Laboratories

Hybrid labs blend physical kits and digital platforms. Students are issued hardware (e.g., Arduino kits) and connect them to cloud-based tools for programming, data sharing, and remote guidance.

- **Features**: Hands-on experimentation, IoT dashboards, cloud-based analytics and collaboration.
- **Advantages**: Encourages self-paced, project-based learning with tangible hardware experience.
- **Limitations**: Depends on internet access and kit availability for students.

Example: The *Arduino IoT Cloud* combined with the Arduino Starter Kit enables students to build and monitor real devices, upload data to the cloud, and conduct remote analyses

—an effective model for teaching embedded systems and IoT fundamentals [26].

This typology offers practical guidance for EEE faculties in Sudan and other low-resource contexts. Institutions can select a model—or a blended combination—based on their curriculum needs, infrastructure, and budget. Combining types often enhances student engagement, access, and practical competency.

Each category of online laboratory offers distinct pedagogical and logistical benefits. Table 1 provides a comparative summary of key features, advantages, and limitations of virtual, remote, hybrid, and AR/VR-enhanced labs to help institutions choose suitable models based on their needs and constraints."

Table 1: Comparative Analysis of Online Laboratory Types

Lab Type	Key Features	Advantages	Limitations
Virtual Labs	Software-based simulations of circuits and systems	- Low cost- Easy to access- Safe learning- Ideal for theory-heavy courses	- No real-world variability- Lacks hands-on tactile experience
Remote Labs	Real hardware accessed via the internet	- High realism- Authentic data- Access to expensive instruments	- Requires strong backend & bandwidth- Limited access windows
Hybrid/Kit-Based Labs	Physical kits (e.g., Arduino) used with online/cloud platforms	- Combines real and digital learning- Encourages project-based learning	- Dependent on student access to hardware- Internet needed for full function
AR/VR-Enhanced Labs	Immersive 3D simulations with interactive controls and visualization	- High engagement and interactivity- Excellent for spatial understanding	- Cost of equipment (VR headsets)- May require high-performance devices

7. REALISM AND INTERACTIVITY

One of the core challenges in online and remote laboratories is the replication of the hands-on, sensory-rich experience that traditional physical laboratories offer. For engineering disciplines such as electrical, mechanical, and civil engineering, tactile engagement with physical components is often critical for developing technical intuition and applied problem-solving skills.

To bridge this gap, emerging educational technologies—particularly **Virtual Reality (VR)** and **Augmented Reality (AR)**—have been integrated into remote laboratory environments. These tools create immersive, three-dimensional simulations that allow students to interact with virtual equipment in ways that closely resemble real-world manipulation.

Through VR headsets or AR-enabled mobile devices, students can perform tasks such as adjusting circuit parameters, probing with virtual instruments, and observing real-time feedback from dynamic systems. These environments not only improve realism but also enhance spatial visualization, conceptual understanding, and learner motivation [27].

In addition, AR/VR platforms make it possible to visualize abstract or normally invisible concepts, such as electromagnetic field distributions, voltage propagation, or system-level energy flows. This capacity significantly enriches the learning experience, particularly in advanced topics that benefit from layered visualization and interactivity.

Figure 3 illustrates a conceptual interface for a VR/AR-enhanced remote laboratory. In this scenario, a student manipulates a virtual multimeter, adjusts resistors or capacitors in a 3D space, and receives real-time feedback on circuit behavior—all while working remotely.

The incorporation of these immersive technologies into online labs represents a major leap in instructional design, particularly for post-conflict or resource-limited contexts like Sudan, where traditional lab access may be restricted but digital transformation opportunities are expanding.

Figure 3: Enhanced Realism via VR/AR Interface

8. AI-DRIVEN ADAPTIVE LEARNING

While remote and online laboratories significantly expand access to engineering education, they also introduce challenges related to student engagement and individualized support. In traditional labs, instructors provide real-time feedback, correct misconceptions, and offer motivational prompts—functions that are often missing in virtual environments. To address this gap, AI-driven adaptive learning systems are being integrated into remote laboratory frameworks.

These systems apply artificial intelligence algorithms to track student interactions, assess performance indicators, and dynamically adjust the learning environment. Data points such as time on task, number of errors, tool usage patterns, and quiz results are analyzed in real time to construct personalized learner profiles [28].

Based on this analysis, adaptive systems can:

- Offer personalized hints, explanations, or simulations.
- Recommend supplemental exercises or targeted review materials.
- Adjust experiment complexity or pacing according to user proficiency.

- Identify and address conceptual misunderstandings early.

This level of personalization benefits students across the performance spectrum: it supports struggling learners with scaffolding and feedback, while challenging advanced learners with progressively difficult tasks. Moreover, AI analytics offer instructors valuable insights into cohort performance, common misconceptions, and usage patterns—facilitating more informed instructional design and intervention strategies.

Figure 4 presents a conceptual architecture of an AI-driven adaptive learning system integrated with a remote lab platform. It includes modules for user tracking, performance analytics, and a feedback engine—all working together to continuously optimize the learner experience.

By embedding AI in remote laboratories, institutions can deliver more responsive, equitable, and scalable learning environments—a critical advancement for education systems operating in post-conflict or resource-constrained settings like Sudan.

9. AVAILABLE TOOLS AND PLATFORMS

The successful implementation of online laboratories requires the selection of appropriate platforms and tools that support experimental interaction, simulation accuracy, real-time control, and pedagogical integration. These tools can be broadly categorized based on their function—simulation environments, remote lab access tools, hardware kits, and integrated educational platforms. Below is an overview of some of the most commonly used tools, both free and commercial, and their relevance to engineering education.

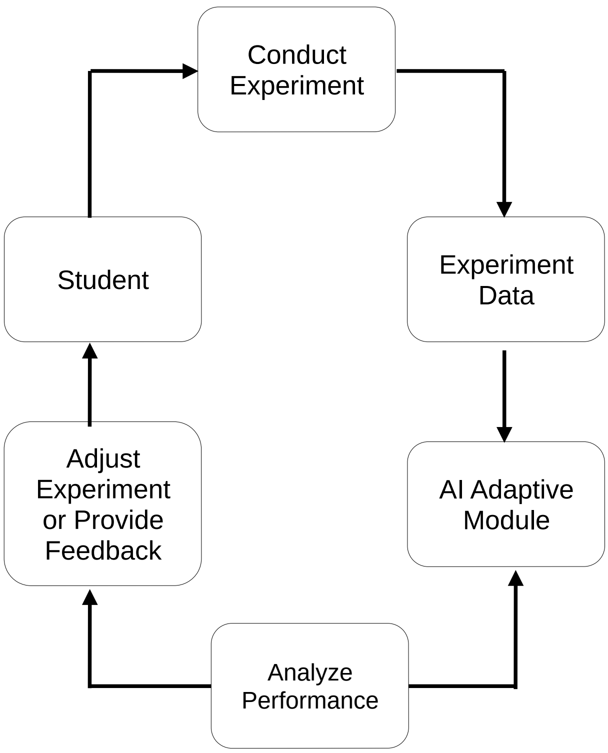

Figure 4: AI-Driven Adaptive Learning Workflow

9.1. Simulation Software

Simulation tools offer virtual laboratory environments where students can design, test, and analyze circuits without physical components.

- **Tinkercad Circuits**
  A user-friendly, browser-based platform ideal for beginners to simulate circuits and program Arduino boards. Offers drag-and-drop simplicity and immediate feedback [23].
- **Multisim Live**
  A powerful circuit simulation tool developed by National Instruments, widely used in academia. It supports both analog and digital electronics, and includes SPICE simulation for realistic analysis [29].
- **MATLAB/Simulink**
  A staple in engineering education, MATLAB provides high-level numerical computing, while Simulink allows for modeling and simulating dynamic systems, including control systems and power electronics [30].
- **Proteus Design Suite**
  A commercial software that combines schematic capture, simulation, and PCB design. It supports co-simulation of microcontroller firmware with circuit behavior [31].

9.2. Remote Lab Platforms

These platforms enable students to access real hardware experiments hosted in university or institutional labs.

- **MIT iLabs**
  A framework that allows universities to host and share experiments globally. Students remotely access instruments like oscilloscopes and function generators through a web interface [5].
- **VISIR (Virtual Instrument Systems in Reality)**
  Focused on electrical and electronic circuit experimentation, VISIR offers a standardized, scalable platform to connect students with physical labs using a virtual interface [21].
- **WebLab-Deusto**
  A remote laboratory platform developed in Spain and used across Europe and Latin America. It offers a wide range of experiments in electronics, control systems, and robotics [32].
- **Labshare (Australia)**
  A distributed infrastructure allowing equipment-sharing across universities. It includes support for experiments in electronics, physics, and telecommunications [33].

9.3. Hardware Kits and IoT Platforms

These are essential for hybrid labs where students interact with physical hardware at home while using cloud services for control and analysis.

- **Arduino and Arduino IoT Cloud**
  Affordable microcontroller kits that allow students to build and program embedded systems. When

connected to the Arduino IoT Cloud, students can monitor and control devices from any location [26].

- **Raspberry Pi**
  A low-cost, credit-card-sized computer that supports remote access and control of sensors, actuators, and cameras. Widely used in IoT and automation projects [34].
- **NI ELVIS (National Instruments Educational Laboratory Virtual Instrumentation Suite)**
  Combines hardware and software for measurements, circuit prototyping, and control system development. Integrated with LabVIEW for virtual instrumentation [35].
- **Blynk**
  A mobile app and cloud platform that allows easy IoT project development and dashboard creation for sensor monitoring and device control [36].

9.4. Open Educational Platforms

These platforms integrate multiple tools into structured course environments and are often used in conjunction with Learning Management Systems (LMS).

- **Virtual Labs India**
  Offers more than 100 interactive labs across disciplines, including electrical circuits, digital electronics, and signal processing. It integrates theory, quizzes, and video tutorials [37].
- **edX and Coursera**
  Host MOOCs with embedded simulations and virtual lab components, allowing learners to engage with experiments in a guided learning environment [22].
- **Moodle and Open edX**
  These LMS platforms can be configured to deliver remote and virtual lab content, manage student submissions, schedule experiments, and provide feedback [38].

These tools form the technological foundation for implementing effective online laboratory education. Their selection depends on factors such as cost, internet bandwidth, technical expertise, and alignment with course objectives. For resource-constrained environments, open-source or hybrid solutions (such as Arduino with online dashboards) offer a promising path forward [39].

10. PEDAGOGICAL BENEFITS

Online laboratories offer a range of educational advantages that enhance teaching and learning experiences in both traditional and remote learning environments. These benefits are especially critical in contexts where physical access to laboratory resources is limited or impossible.

1. Accessibility:

Online labs break down geographical and temporal barriers, allowing students to engage in laboratory activities from anywhere with an internet connection. This is particularly valuable for students in remote areas, conflict zones, or during global disruptions like pandemics[1]. Learners can repeat experiments at their own pace and schedule, catering to diverse learning styles and needs[40].

2. Cost-effectiveness:

Virtual labs reduce or eliminate the need for expensive equipment, consumables, and laboratory maintenance[41]. Educational institutions can offer high-quality, interactive lab experiences without the financial burden of purchasing and updating physical tools and materials. This democratizes access to STEM education by lowering infrastructure costs[42].

3. Scalability:

Unlike physical labs that have limited space and resources, online labs can accommodate hundreds or even thousands of students simultaneously[43]. This makes them ideal for large-scale educational programs, open online courses (MOOCs), and institutions with growing student populations.

4. Safety:

Online laboratories provide a risk-free environment for students to explore complex or hazardous experiments[44]. This ensures that learners can practice procedures, make mistakes, and understand consequences without any threat to their personal safety or to costly equipment. It is especially beneficial when dealing with dangerous chemicals, high voltages, or biohazards.

Overall, online laboratories not only replicate essential hands-on experiences but also provide a flexible, inclusive, and pedagogically rich learning environment that prepares students for both academic and professional success.

11. CHALLENGES AND LIMITATIONS

While online laboratories offer a wide array of opportunities for enhancing engineering education, their adoption and effective implementation come with notable challenges. These challenges vary by region, institutional capacity, and infrastructure availability. In the context of Sudan and similar developing countries, they are often magnified by political, economic, and technological constraints. Understanding these limitations is essential for designing realistic, sustainable strategies.

11.1. Technical Infrastructure and Connectivity

One of the foremost challenges is the lack of reliable and high-speed internet, particularly outside major urban centers. Many rural areas still suffer from frequent power outages and limited access to computers or modern smartphones.

Bandwidth-intensive tools such as remote labs and 3D simulations may be inaccessible to students in low-connectivity areas.

Server hosting and data storage for real-time lab environments often require cloud infrastructure, which may be unavailable or unaffordable.

Mitigation Strategy

Prioritizing lightweight simulation tools and offline-compatible platforms is crucial. Partnerships with telecom companies or NGOs to subsidize internet access for students can also alleviate this issue.

11.2. Financial Constraints

Developing online lab infrastructure—especially remote access to physical instruments—can be capital-intensive. The cost of setting up, maintaining, and upgrading servers, instruments, software licenses, and security systems is substantial.

Institutions may struggle to fund initial investment in platforms like VISIR or NI ELVIS.

Many high-quality platforms require paid licenses, putting them out of reach for public universities with constrained budgets.

Mitigation Strategy:

Adopting open-source tools (e.g., Tinkercad, WebLab-Deusto) and using low-cost microcontroller kits (e.g., Arduino, Raspberry Pi) can reduce costs. Shared lab initiatives among institutions can also distribute expenses.

11.3. Lack of Technical Skills and Faculty Training

Faculty members (academic staff) may not be fully equipped to design, manage, and assess online lab activities. Similarly, students may need time to adapt to new interfaces and workflows.

Resistance to change may exist due to unfamiliarity with remote tools.

Curriculum designers may lack experience integrating virtual labs with course outcomes.

Mitigation Strategy:

Capacity-building workshops, continuous professional development programs, and peer mentoring can support instructors in this transition. Including digital lab training in the undergraduate curriculum prepares students early.

11.4. Pedagogical Challenges

While simulations and remote access can offer flexibility, they often lack the tactile, sensory, and hands-on experiences critical to engineering education. The inability to physically handle components or troubleshoot connections may limit skill acquisition.

1. Certain skills, such as soldering or cable management, are difficult to teach remotely.
2. Student engagement and collaboration may decline without proper instructional design.

Mitigation Strategy:

Blended models that combine online labs with occasional in-person workshops can bridge this gap. Virtual tools should also include interactive tutorials, guided problem-solving, and feedback loops to enhance engagement.

11.4. Curriculum Integration and Accreditation

Incorporating online labs into existing curricula requires alignment with learning outcomes, institutional approval, and possibly national accreditation body endorsement.

1. Misalignment may lead to redundancy or loss of essential competencies.
2. Lack of official recognition may discourage their widespread adoption.

Mitigation Strategy:

Pilot programs should be developed in collaboration with curriculum developers and accreditation boards to ensure compliance. Documentation of student outcomes and comparative studies can support advocacy for broader acceptance.

11.5. Security and System Reliability

Online laboratories, especially remote access to hardware, are vulnerable to cyberattacks, misuse, and system failures.

1. Unauthorized access can damage equipment or compromise data.
2. Downtime or maintenance issues can disrupt learning schedules.

Mitigation Strategy:

Strong authentication, role-based access, and redundant system design are essential. Regular system audits and student orientation on responsible use also help maintain stability and security.

These challenges are not insurmountable. With proper planning, phased implementation, and regional collaboration, many of these limitations can be mitigated or even turned into opportunities for innovation. Awareness and transparency about these issues are essential for policymakers, educators, and donors involved in modernizing engineering education in Sudan and similar settings.

12. APPLICATIONS IN SUDAN

Sudan faces profound challenges in delivering quality engineering education due to decades of underinvestment in educational infrastructure, economic hardship, and more recently, the destruction caused by armed conflict. Traditional electrical and electronic engineering laboratories, which require physical space, expensive equipment, and stable utilities, have been among the hardest hit. In this context, online laboratories represent a strategic solution—one that can mitigate existing limitations while enabling innovation in pedagogy and resource allocation.

To guide strategic planning, a SWOT analysis is presented in Table 2, summarizing the internal strengths and weaknesses, as well as external opportunities and threats related to the implementation of online laboratories in Sudan."

12.1. Educational Context and Needs

Many engineering faculties in Sudan operate without fully functional laboratories. Students often graduate with strong theoretical knowledge but limited practical experience. This creates a skills mismatch in the job market and limits graduates' competitiveness in regional or global engineering sectors.

- **Overcrowded classrooms** and limited lab access time reduce the effectiveness of hands-on learning.

- **Inequity between urban and rural institutions** widens the educational gap, with some universities lacking any functional labs.
- **High cost of lab equipment imports** and foreign currency shortages make updating facilities difficult.

In this setting, online laboratories can democratize access to practical training, ensuring that all students—regardless of location or institutional wealth—receive a baseline level of experimental exposure.

Table 2: SWOT Analysis – Implementing Online Labs in Sudan

Strengths	**Weaknesses**
- Strong theoretical foundation in EEE curricula	- Poor internet connectivity in many areas
- Increasing awareness of digital tools among youth	- Limited faculty training in online labs
- Potential support from diaspora and international partners	- High upfront costs for remote lab setup
- Growing interest in renewable energy and IoT-based projects	- Fragmented post-conflict educational infrastructure
Opportunities	**Threats**
- Use of low-cost kits (Arduino, Raspberry Pi)	- Continued political instability and security concerns
- Phased implementation tailored to context	- Risk of digital divide (urban vs rural, male vs female students)
- Leverage mobile-based platforms for AR/VR or dashboards	- Dependence on external funding or donor-driven timelines
- Regional collaboration with African and Arab universities	- Brain drain of technical talent

12.2. Phased Adoption Strategy

A practical model for implementation in Sudan involves a **three-phase rollout** aligned with the current educational infrastructure and funding constraints:

Phase 1: Virtual Labs (Simulations)

- Begin with low-cost or free platforms such as Tinkercad, Multisim Live, and PSpice for Education.
- Integrate simulations into existing coursework in electronics, circuit theory, and digital systems.
- Develop instructor-led sessions and video tutorials in Arabic to support adoption and accessibility.
- Collaborate with diaspora academics and local graduates to create Sudan-specific content.

Phase 2: Hybrid and Local Kit-Based Labs

- Use microcontroller-based kits (e.g., **Arduino**, **ESP32**) that can be assembled and maintained locally.
- Develop remote-access interfaces for select kits using open-source platforms (e.g., **Blynk**, **ThingSpeak**).
- Encourage student innovation by introducing project-based modules, e.g., solar charging systems or sensor networks relevant to Sudan's development needs.

Phase 3: Remote Labs with Shared Infrastructure

- Establish central lab hubs at leading universities (e.g., University of Khartoum, Sudan University of Science and Technology).
- Enable remote access to actual lab equipment through national academic networks.
- Use cloud dashboards and scheduling systems to facilitate safe, timed student interactions with instruments like oscilloscopes, function generators, and power supplies.

This phased strategy reduces dependency on large upfront investments and creates pathways for long-term sustainability.

12.3. Institutional and Policy Support

The successful implementation of online labs in Sudan will require **multi-level coordination**:

- **Universities** must revise curricula to integrate online lab components and train instructors in digital pedagogy.
- **The Ministry of Higher Education** should issue policies recognizing online labs as valid alternatives to physical labs, particularly in emergency or conflict-affected settings.
- **International donors and NGOs** (e.g., UNESCO, DAAD, Education Cannot Wait) can provide funding, technical assistance, and access to global lab-sharing platforms.

12.4. Opportunities for Innovation and Inclusion

Online labs in Sudan also open avenues for:

- **Gender inclusion**, allowing more female students—especially in conservative or rural communities—to participate in engineering labs from home.
- **Refugee and displaced student education**, ensuring continuity of learning despite war or displacement.
- **Entrepreneurship and local industry collaboration**, where students can prototype, test, and deploy practical solutions in agriculture, health, and energy using digital tools.

Online laboratories are not just a temporary substitute in Sudan—they offer a transformative opportunity to reimagine engineering education as more accessible, resilient, and inclusive. With vision and investment, Sudan can position itself at the forefront of digital engineering education in Africa.

13. CONCLUSION

Online and remote laboratories represent transformative opportunities for engineering education in Sudan, particularly given the challenges of conflict and under-investment in traditional infrastructure. This paper proposes a tailored three-phase implementation roadmap—from low-cost virtual simulations, through hybrid hardware-cloud models, to a national network of remote labs hosted by universities—supported by a SWOT analysis that highlights Sudan's internal strengths and external challenges. Effective realization of this strategy requires coordinated national efforts: universities must update curricula and adopt digital pedagogy, the Ministry of Higher Education should formally recognize online labs, and international donors and the Sudanese academic diaspora need to contribute resources and expertise. By embracing this approach, Sudan can modernize its engineering education system, making it more inclusive, resilient, and aligned with future needs. The moment to act is now.

AI Writing Disclosure

The author used ChatGPT (OpenAI) to assist with drafting and improving the clarity of this manuscript. All content was reviewed and edited, and the author assumes full responsibility for its accuracy and originality.

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APPENDIX A

Table A1: Implementation Toolkit for Sudanese Institutions

Phase	Tools & Platforms	Key Activities	Local Adaptation Strategies
Phase 1: Virtual Labs	Tinkercad, Multisim Live, PSpice for Education	Integrate simulations into existing electronics and circuit courses; deliver tutorials	Offline-ready materials; localize content with diaspora collaboration
Phase 2: Hybrid/Kit-Based Labs	Arduino, ESP32 kits, Blynk, ThingSpeak	Distribute kits; assign embedded systems and IoT projects	Source components locally; use projects relevant to Sudan (e.g., solar, water)
Phase 3: Shared Remote Labs	VISIR, MIT iLabs, national university server	Set up control systems and scheduling; train academic staff member; build shared lab hubs	Locate central labs at UofK develop MOUs among universities

Table A2: Cost Estimate Overview (Typical Ranges)

Item	Estimated Cost (USD)
Student Arduino Kit	35–50
Raspberry Pi Setup	60–80
Remote Lab Server Setup	2,000–5,000
Cloud Dashboard Licensing (Annual)	500–2,000
Faculty Training Workshops (Per Cohort)	1,000–3,000
Video Tutorial Development (Per Course)	300–800

This toolkit can guide EEE departments, policymakers, and international partners in designing scalable and cost-effective lab strategies tailored to Sudan's realities (also referenced in Sections 4B, 4C, and 12).