**Can Modular Chemical Plants Lower the Barriers to African Industrialization? A Systematic Review Study**

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**Abstract**

This study explores the potential of modular chemical plants (MCPs) to mitigate existing barriers to industrialization within Africa's chemical sector. Employing a Systematic Literature Review (SLR) methodology, this study rigorously identifies, evaluates, and synthesizes findings from peer-reviewed academic studies and authoritative industry reports. Key barriers to African industrialization, including financial constraints, infrastructural deficits, skills shortages, and policy inconsistencies, are analyzed in the context of the chemical industry. The techno-economic advantages of MCPs, such as reduced capital expenditure, accelerated project timelines, enhanced locational flexibility, and improved safety, are systematically evaluated against these barriers. The analysis further explores the role of process intensification (PI) within modular systems and the implications of "economies of numbers" versus traditional "economies of scale." Case studies of modular plant applications in developing countries, including relevant examples from Africa in sectors like chlor-alkali, gas-to-liquids (GTL), fertilizers, and water treatment, are examined to provide empirical context. The findings suggest that MCPs offer a compelling, albeit not universal, pathway to de-risk investments, enable localized value addition to Africa's natural resources, and foster a more adaptable and resilient chemical manufacturing base, thereby offering a significant opportunity to lower several critical barriers. This study contributes a nuanced, evidence-based perspective on a novel technological approach to a critical development challenge.

**Keywords:** *Modular Chemical Plants, African Industrialization, Chemical Manufacturing, Systematic Literature Review, Barriers to Industrialization, Process Intensification, Sustainable Development.*

**1.0. Introduction**

Africa's pursuit of industrialization is a cornerstone of its developmental aspirations, prominently featured in continental frameworks such as the African Union's Agenda 2063.1 This long-term vision aims to establish a prosperous Africa, based on inclusive growth and sustainable development, identifying industrialization as a primary engine for economic transformation, comprehensive job creation, and significant poverty alleviation.3 Within this broad industrialization agenda, the chemical sector assumes a foundational and catalytic role. It serves as a linchpin industry, supplying essential inputs and intermediates to a wide array of other economic sectors, including agriculture (fertilizers, pesticides, herbicides), manufacturing (plastics, solvents, additives), construction (adhesives, sealants, coatings), pharmaceuticals (Active Pharmaceutical Ingredients - APIs, excipients), and consumer goods (detergents, personal care products).3 Consequently, the maturation and expansion of the chemical industry are pivotal for achieving broader economic diversification, enhancing local value addition, and improving overall economic resilience on the continent.

Despite this recognized importance, Africa's chemical manufacturing sector remains significantly underdeveloped, contributing a disproportionately small share estimated at less than 2% to global chemical manufacturing value added.7 This underdevelopment has led to a pronounced and often precarious reliance on imports for a wide array of essential chemical products, worth $56 billion in 2021.8 Such import dependency not only drains foreign exchange reserves but also exposes African economies to the vagaries of global price volatility and disruptive supply chain shocks, as starkly highlighted during the COVID-19 pandemic.10 Conversely, the development of robust local chemical production capabilities offers substantial socio-economic benefits, from job creation across skill levels to boosting exports and driving innovation through R&D. It supports critical development goals, such as improving food security with local fertilizers and enhancing public health through accessible pharmaceuticals. The chemical sector's underdevelopment, therefore, is not merely a symptom of broader industrial challenges but acts as a significant bottleneck to achieving the ambitious socio-economic aspirations outlined in Agenda 2063.

However, the development of Africa’s chemical sector is impeded by a complex web of interconnected barriers that hinder its ability to attain its potential. The inherently capital-intensive nature of chemical plants demands substantial upfront investment, posing a formidable challenge in economies with limited access to affordable long-term finance, especially for Small and Medium-sized Enterprises (SMEs).9 High debt burdens, high inflation, and currency volatility compound financial risks, with 32% of African firms identifying limited access to finance as a major barrier to growth. In 2023, nearly half of African nations exhibited debt-to-GDP ratios exceeding 60%, with a considerable portion of government revenue diverted to debt servicing.9 Low domestic purchasing power further constrains market demand for locally produced chemicals. Market access is particularly constrained by fragmentation and significant non-tariff barriers that impede intra-African trade.9 Achieving economies of scale with conventional large plants is difficult when domestic or regional markets are small (fragmented) or logistical costs for distribution are prohibitively high.

Inadequate infrastructure is another critical bottleneck. Unreliable and expensive electricity supplies affect energy-intensive processes, while poor transportation networks dramatically increase logistics costs and complicate moving hazardous materials.4 Indeed, infrastructure gaps contribute to trade costs in Africa being approximately 50% higher than the global average.9 The continent also faces a significant shortage of skilled labor, particularly chemical engineers, process technicians, and specialized maintenance personnel. Educational systems struggle to produce graduates with industry-relevant skills, and a digital skills gap hinders adopting crucial 4th Industrial Revolution technologies. Political instability, governance challenges, corruption, outdated or inconsistent regulatory frameworks, bureaucratic hurdles, and a lack of coherent long-term industrial policies further deter investment and create uncertainty.

These barriers are not isolated. They are deeply interconnected, creating a stifling cycle wherein poor infrastructure inflates costs, deterring investment, which limits opportunities for upgrades, skills development, and technology adoption.

Against this backdrop of complex challenges, Modular Chemical Plants (MCPs) emerge as an innovative technological and strategic approach that could potentially alter the trajectory of chemical industry development in Africa. MCPs are processing facilities constructed by fabricating individual process units (comprising equipment, piping, instrumentation, and control systems) on steel frames known as skids or modules in a controlled off-site workshop.11 These prefabricated modules are then transported to the site for interconnection and integration, parallelizing construction, improving quality control, and reducing on-site time and complexity.20 This approach offers several purported advantages pertinent to the African context, including lower upfront capital expenditures compared to traditional stick-built plants, shorter project execution times, enhanced flexibility in plant siting (including remote locations)11, and the ability to scale production incrementally by adding modules to offer a dynamic response to evolving market demands.19

Consequently, MCPs present Africa with an alternative construction methodology and a fundamental shift in chemical industry development. They represent a decisive move from the traditional high-risk, capital-intensive, slow-return model towards an agile, adaptable, and potentially less costly pathway. This is particularly relevant to the concept of "leapfrogging," where developing economies bypass older, less efficient technological stages to adopt more advanced solutions.22

Essentially, the inherent characteristics of modularization (reduced initial CAPEX, faster deployment, and suitability for distributed resources) may fundamentally alter the risk-reward calculus for chemical industry investments in Africa, potentially making chemical production accessible to a broader range of entrepreneurs and investors, including domestic SMEs.

1.1. Research Questions and Objectives

This exploratory study seeks to address the central question: *Can Modular Chemical Plants lower the barriers to African Indusstrialization, with a focus on Africa's chemical sector?* Should the evidence suggest an affirmative answer, a subsequent question will be investigated: *To what extent can modularization help African industrialization, both qualitatively and quantitatively?*

The study aims for an exploratory yet rigorous scientific investigation, providing a nuanced understanding of the opportunities and challenges associated with leveraging modular chemical plant technology for African industrial advancement. Specific objectives are as follows:

1. To systematically review and synthesize existing literature on modular chemical plant technology and the prevailing conditions for industrialization in Africa's chemical sector.
2. To critically evaluate the potential of MCPs to mitigate the identified barriers to industrial development within Africa's chemical industry.
3. To provide an evidence-based, objective answer to the primary research question.
4. If the potential is affirmed, to assess the prospective scale, scope, and nature of modularization's contribution to the industrialization of Africa's chemical sector.
5. To identify key considerations, including techno-economic feasibility, policy frameworks, human capital development, and risk factors, pertinent to the adoption of MCPs in Africa.
6. To delineate areas for future research and suggest potential strategic implications for policymakers and industry stakeholders.

1.2. Significance and Contribution of the Study

This study’s contribution is its focused and systematic exploration of how modularization can address the specific constraints of chemical manufacturing in Africa, an intersection that remains underexplored in existing literature. By aligning the unique capabilities of modular technologies with Africa’s industrial realities, it provides valuable insights for policymakers, investors, technology developers, and researchers.

**2.0. Methods**

This study employs a Systematic Literature Review (SLR) methodology to address the research questions. The SLR approach is chosen for its rigorous, transparent, and replicable process of identifying, critically appraising, and synthesizing all relevant existing evidence pertaining to a clearly formulated question.24 This methodology is particularly suited for an exploratory yet scientific investigation that aims to provide an objective answer based predominantly on peer-reviewed academic research and other credible sources. The SLR allows for a comprehensive mapping of the current knowledge landscape, identification of consistencies and contradictions in findings, and the delineation of research gaps.24 Given that the intersection of "modular chemical plants" and "African industrialization" represents an emerging and interdisciplinary field, an SLR is essential for systematically gathering and integrating potentially fragmented evidence from diverse sources.

The conduct and reporting of this SLR adheres to the guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement.45

2.1. Search Strategy

A comprehensive and systematic search strategy was developed and executed to identify all relevant literature pertaining to modular chemical plants, African industrialization, the chemical sector in Africa, and associated techno-economic analyses.

* + 1. *Databases Searched*

The search encompassed major academic and scientific databases, including Scopus, Web of Science (Core Collection), Compendex (Engineering Village), American Institute of Chemical Engineers (AIChE) Online Library, American Chemical Society (ACS) Publications, and Google Scholar. Additionally, grey literature was sourced from institutional repositories such as UNIDO, AfDB, World Bank, UNECA, African Union, McKinsey & Company, and other consulting and policy institutions with a focus on African industrial development and chemical process economics.

* + 1. *Search Terms and Keywords*

Search terms were developed based on key facets of the research question and grouped into clusters. Boolean operators (AND, OR) were used to combine these terms.

**Cluster 1 (Modular Plants):** "modular chemical plant\*", "modular process plant", "skid-mounted plant", "containerized plant\*", "small-scale chemical production", "small scale chemical plant", "decentralized chemical production", "distributed chemical manufacturing", "process intensification", "modular construction", "prefabricated plant\*", "numbering-up"

**Cluster 2 (Africa/Developing Countries):** "Africa\*", "Sub-Saharan Africa", "developing country", "emerging economy", "LDC" (Least Developed Countries), "low-income country", "middle-income country"

**Cluster 3 (Industrialization/Chemical Sector):** "industrialization", "industrial development", "industrial policy", "manufacturing", "chemical industry", "chemical sector", "chemical manufacturing", "petrochemical", "fertilizer", "agrochemical", "pharmaceutical", "polymer", "specialty chemical", "fine chemical", "water treatment chemical", "gas-to-liquids", "GTL", "chlor-alkali", "biomass conversion"

**Cluster 4 (Barriers/Drivers/Enablers):** "barrier", "challenge", "obstacle", "constraint\*", "driver", "enabler", "opportunity", "potential", "factor"

**Cluster 5 (Techno-economics/Impact/Feasibility):** "techno-economic analysis", "TEA", "economic feasibility", "economic evaluation", "cost-benefit analysis", "NPV" (Net Present Value), "IRR" (Internal Rate of Return), "ROI" (Return on Investment), "capital cost", "CAPEX", "operating cost", "OPEX", "economic impact", "value chain", "supply chain", "technology adoption", "technology transfer", "risk assessment", "policy framework"

The search strategy also involved snowballing techniques, where reference lists of identified key articles and reviews were manually scanned for additional relevant publications.

2.2. Inclusion and Exclusion Criteria

To ensure the relevance and quality of the literature included in this systematic review, a predefined set of inclusion and exclusion criteria was applied during the screening process.

* + 1. Inclusion Criteria

1. **Study Types:** Peer-reviewed journal articles, book chapters, full conference papers from reputable conferences, and substantive technical reports from recognized international organizations and consulting firms (e.g., World Bank, UNIDO, AfDB, AU, UNECA, McKinsey) or national government bodies.
2. **Content Focus**:
3. Studies discussing modular chemical or process plants, including their design, construction, operation, economics, or application.
4. Studies addressing industrialization in Africa, with a particular focus on the chemical sector, its barriers, drivers, or potential.
5. Techno-economic analyses (TEA), cost-benefit analyses (CBA), or economic feasibility studies of modular plants, especially in developing country or African contexts.
6. Case studies of modular plant implementation or pilot projects in relevant sectors (e.g., petrochemicals, fertilizers, pharmaceuticals, agrochemicals, water treatment, GTL, mini-refineries, biomass conversion) in developing countries or Africa.
7. Policy discussions, regulatory analyses, or strategic frameworks related to industrial technology adoption, particularly modular systems, in Africa or developing economies.
8. Studies on process intensification (PI) if explicitly linked to modular systems or small-scale chemical production.
9. **Relevance:** Studies that directly address or provide substantial evidence relevant to the research questions.
10. **Language:** Studies published in English.
11. **Timeframe:** Primarily studies published from January 2000 to May 2025 were included. This timeframe was chosen to capture the most current advancements in modular technology, process intensification, and contemporary analyses of African industrialization. Seminal earlier works on modular concepts or process intensification were considered for inclusion if they were highly cited and foundational to the current understanding of the topic.

2.2.2. Exclusion Criteria

1. Editorials, opinion pieces, book reviews, abstracts-only, or non-substantive short communications (unless they led to a full eligible study).
2. Studies not available in English.
3. Studies focused purely on modularity in non-chemical/non-process industries (e.g., building construction, software) unless they presented generalizable principles of modular economics or logistics clearly applicable to industrial plants.
4. Purely theoretical modeling studies without empirical validation, strong analytical grounding relevant to the research questions, or clear application to chemical processing.
5. Studies with insufficient methodological detail, transparency, or data to allow for a reasonable quality appraisal or to extract meaningful information relevant to the review.
6. Duplicate publications of the same study.

2.3. Analytical Framework

The analytical framework for this SLR involved a systematic mapping of the characteristics, advantages, and disadvantages of MCPs (derived from the literature) against the identified barriers to industrialization in Africa's chemical sector. The primary analytical approaches included:

* **Thematic Analysis:** Qualitative data from the studies were coded and analyzed to identify recurring themes, patterns, concepts, and relationships concerning the benefits and challenges of modularity, barriers to African industrialization, and potential linkages. This involved identifying common arguments, supporting evidence, and divergent viewpoints.
* **Narrative Synthesis:** Findings from diverse studies were integrated and woven into a coherent narrative to address the research questions. This involved summarizing key findings, comparing and contrasting results, and explaining variations across different contexts or study types.
* **Comparative Analysis:** Where appropriate, findings were compared across different chemical sub-sectors, types of modular technologies, or geographical regions within Africa to identify specific contexts where modularity might offer greater or lesser potential.
* **Quantitative Analysis (where data permitted):** While a formal meta-analysis of techno-economic data was anticipated to be challenging due to the expected heterogeneity in study methodologies, assumptions, and reporting standards, efforts were made to summarize and compare quantitative data (e.g., ranges of cost savings, schedule reductions, investment figures for case studies) where feasible. This specifically involves summarizing and comparing reported techno-economic data from case studies and feasibility analyses, and examining metrics like percentage cost reduction, schedule compression, NPV, IRR, and payback periods.
* **Systems Thinking/Pattern Recognition:** Identifying interconnections between MCP features and their potential impacts on the complex system of African industrialization. This involved looking for patterns in how specific modular attributes (e.g., lower capital cost, faster deployment, flexibility) could interact with and alleviate specific constraints (e.g., financial limitations, infrastructure deficits, market uncertainties).

Where quantitative meta-analysis was limited, the synthesis focused on drawing robust qualitative conclusions and identifying consistent patterns of reported benefits and addressed challenges.

**3.0 Results and Discussion of Results**

*The systematic literature review process, initiated with a broad search across multiple academic and grey literature databases, yielded an initial pool of 2,874 records after deduplication. Following a rigorous title and abstract screening, 243 articles were deemed potentially relevant and subjected to full-text review against the predefined inclusion and exclusion criteria. Of these, 76 studies were ultimately selected for inclusion in this systematic review.*

3.1. Fundamentals of Modular Chemical Plants

Modular Chemical Plants (MCPs) represent a significant departure from traditional stick-built construction methodologies. They are process systems constructed through the assembly of pre-fabricated, self-contained units, often referred to as modules or skids.27 These pre-fabricated and pre-tested modules are then transported to the designated plant location for final interconnection, integration with site utilities, and commissioning.11 Modules can vary in complexity, ranging from individual process units (such as reactors, distillation columns, or filtration systems) to complete sections of a plant encompassing multiple unit operations.

Several core concepts underpin the modular plant philosophy:

* **Process Intensification (PI):** PI involves the development and application of novel chemical engineering principles and technologies that lead to substantially smaller, cleaner, safer, and more energy-efficient processes.34 PI techniques aim to improve heat and mass transfer, combine multiple unit operations (e.g., reaction and separation) into single pieces of equipment, or utilize alternative energy sources. The inherent compactness achieved through PI is highly synergistic with modularization, leading to what is termed Modular Chemical Process Intensification (MCPI).34 MCPI allows for complex chemical processes to be housed in smaller, more efficient, and easily transportable modules.
* **Design for Manufacture and Assembly (DfMA):** DfMA is a systematic design approach that focuses on simplifying product design to make components easier and more cost-effective to manufacture and easier to assemble.27 This is a crucial design philosophy that prioritizes ease of manufacturing for the individual components of a module and efficiency in the subsequent assembly of these components into a functional unit, as well as the final assembly of modules on site.8 This includes considerations for material selection, standardization of parts, minimization of part counts, and ease of connection.
* **Advanced Manufacturing Techniques:** The fabrication of modules increasingly leverages advanced manufacturing techniques such as automation, robotics, and digital technologies.27 Building Information Modeling (BIM), digital twins, and advanced simulation tools are used for detailed design, clash detection, fabrication planning, and lifecycle management of modular plants.
* **Standardization:** Standardization of module designs, dimensions, equipment, and particularly interfaces is a key enabler for achieving cost-effectiveness, reusability, and interchangeability of modules.9 Standardized interfaces are fundamental to the "plug and produce" or "plug and operate" capability, allowing modules to be easily connected, disconnected, or reconfigured.9 However, the lack of universally adopted industry-wide standards for chemical process modules remains a significant challenge, often necessitating custom designs.9
* **Numbering-up vs. Scale-up:** For capacity expansion, modular plants often employ a numbering-up strategy (i.e., adding identical, parallel modules) as opposed to the traditional scale-up approach (i.e., designing and constructing a single, larger-capacity unit).9 Numbering-up offers significant flexibility in matching production capacity to market demand incrementally. This paradigm allows for smaller initial investments and capacity additions only when justified, reducing upfront risk, especially in uncertain or nascent markets. However, the economic trade-offs between numbering-up (potential for increased complexity in managing multiple units) and scale-up (traditional economies of scale) require careful evaluation for specific products and market sizes.9
* **Skid-Mounted Systems vs. Containerized Plants:** Skid-mounted modular plants are self-contained process systems built on a structural steel base (skid), allowing for easy transport and integration. In contrast, containerized plants are designed to fit within standard shipping containers, making them especially suited for deployment in remote or logistically challenging locations.

Other core concepts associated with modular plants include *interchangeability* (designing modules that can be easily replaced or upgraded), and *equaling-up* (combining modules of different standard sizes to achieve desired capacity).30

The learning effect associated with modular construction, where the cost per module decreases with cumulative production experience32, offers a significant long-term strategic advantage. If Africa can develop regional centers for module fabrication, this learning curve could benefit numerous projects across the continent. This implies that while initial projects might incur higher costs associated with pioneering the technology in a new region, subsequent projects could become increasingly cost-competitive, fostering a self-sustaining local or regional advanced manufacturing capability. This represents a profound implication for regional industrial strategy, moving beyond simply importing modules to cultivating a domestic industry.

Furthermore, the synergy between MCPI and modularity is a critical factor. Process intensification makes modules significantly smaller, more efficient, and often safer. In turn, modularity makes the deployment of these advanced PI technologies more feasible, less risky, and more adaptable to varying scales and locations. This combination is central to the "leapfrogging" potential, allowing developing economies to bypass older, less efficient, and more capital-intensive conventional technologies.40 PI technologies often involve novel equipment and process configurations39; implementing these directly into a large, traditional stick-built plant for the first time can be a high-risk, high-cost endeavor. MCPI34 allows these advanced PI units to be developed, tested, and proven at a smaller, modular scale, thereby reducing both technical and financial risks. The compactness derived from PI then makes the resulting modules easier and less expensive to transport and install. This symbiotic relationship is considerably more powerful than either modularity or PI implemented in isolation.

To provide a clearer comparative context, Table 1 summarizes the key characteristics, advantages, and disadvantages of modular versus conventional chemical plant construction approaches.

Table 1: *Comparison of Modular and Conventional Chemical Plant Construction Approaches*

|  |  |  |
| --- | --- | --- |
| **Feature** | **Modular Chemical Plants** | **Conventional (Stick-Built) Chemical Plants** |
| **Construction Site** | Primarily off-site factory fabrication of modules; on-site assembly and integration.28 | Entirely on-site construction from individual components and materials.34 |
| **Design Philosophy** | Standardized modules, DfMA principles, emphasis on transportability and interconnectivity.27 | Custom, site-specific design, often optimized for large scale.32 |
| **Scale** | Well-suited for small to medium scale; scalable by adding modules (numbering-up).32 | Typically designed for large to very large scale to achieve economies of scale.32 |
| **Flexibility** | High flexibility to market changes, phased investment, potential for relocation.32 | Low flexibility once constructed; capacity changes are difficult and costly. |
| **Typical Project Timeline** | Significantly shorter due to parallel activities (12-18 months often cited for smaller units).27 Reduced weather delays. Build times are generally reduced by 25-50%. | Longer, sequential construction phases (can be several years).33 Susceptible to weather delays. |
| **Capital Cost Profile** | Generally lower upfront investment, especially for small to medium scale. Potential 10 to 30% total project cost reduction.32 | High upfront CAPEX; benefits from economy of scale (six-tenths rule) for very large capacities.32 |
| **On-site Labor** | Reduced on-site labor, shift towards assembly and integration skills.28 | Large, diverse on-site construction workforce required for extended periods. |
| **Time-to-Market** | Faster, allowing earlier revenue generation. | Slower. |
| **Locational Flexibility** | High. Suitable for remote areas, proximity to resources/markets. Transportable/relocatable. | Low. Requires extensive site infrastructure and resource access. |
| **Safety (Construction Phase)** | Enhanced due to controlled factory environment for module fabrication. | Higher risks associated with on-site construction (working at height, weather, etc.). |
| **Safety (Operation - Hazardous Materials)** | Potential for reduced risk by point-of-use production, smaller inventories per site. | Larger inventories, risks associated with bulk transport of hazardous materials. |
| **Quality Control** | Improved due to factory fabrication standards and testing. | More variable, dependent on on-site conditions and practices. |
| **Quality Control** | Higher and more consistent quality due to controlled factory fabrication environment.27 | On-site quality control can be more variable, subject to site conditions and workforce skill.29 |
| **Waste Generation** | Less on-site construction waste; optimized material use in factory.28 | Higher potential for on-site construction waste. |
| **Locational Flexibility** | High. Suitable for remote areas, proximity to resources/markets. Transportable/relocatable. | Low. Requires extensive site infrastructure and resource access.19 |
| **Safety (Construction Phase)** | Enhanced due to controlled factory environment for module fabrication. | Higher risks associated with on-site construction (working at height, weather, etc.).19 |
| **Safety (Operation - Hazardous Materials)** | Potential for reduced risk by point-of-use production, smaller inventories per site. | Larger inventories, risks associated with bulk transport of hazardous materials.19 |
| **Upfront Engineering (FEED)** | Often requires more detailed engineering upfront before fabrication. | Design can evolve more during construction. |
| **Process Intensification (PI) Integration** | Highly compatible; PI leads to smaller units ideal for modularization (MCPI). | Can be retrofitted, but PI is often more seamlessly integrated in new modular designs.11 |

3.2. Analysis of Barriers to Africa's Chemical Sector Industrialization

The literature review confirms a consistent set of significant, often interlinked, barriers that impede the growth and development of the chemical sector across many African countries. These are detailed below.

#### 3.2.1. Economic and Financial Constraints

The establishment of chemical industries is a capital-intensive endeavor. A primary barrier identified is the **high upfront capital cost** associated with traditional, large-scale chemical plants.9 This is compounded by **limited access to affordable finance**, especially for local Small and Medium-sized Enterprises (SMEs), which often form the backbone of nascent industrial sectors.9 Financial markets in many African countries are characterized by high interest rates, stringent collateral requirements, and a general aversion to long-term industrial project financing. In 2023, 32% of African firms cited limited access to financial tools as a major obstacle to growth.11 High sovereign debt levels in many nations 9 also constrain public investment in industrial infrastructure and support. Furthermore, macroeconomic instability, including currency volatility and persistent inflation 9, increases investment risk and can erode project profitability. The low purchasing power of large segments of the population in some regions can also limit the domestic market size for chemical products, thereby affecting the perceived viability of new ventures.7 The terms of finance available are often unsuitable for long-gestation industrial projects, with high-risk premiums making capital prohibitively expensive. This financial landscape makes technologies that can reduce perceived risk or shorten payback periods particularly attractive.

#### 3.2.2. Infrastructural Deficiencies (Energy, Transport, Logistics)

Infrastructural gaps are a critical impediment to chemical sector development in Africa.3

* **Energy:** The chemical industry is often energy-intensive, yet many African countries suffer from an **unreliable and costly electricity supply**.4 Less than half of the African population has access to reliable electricity, and dependency on fossil fuels makes industries vulnerable to price shocks.9 Frequent power outages disrupt production and increase operational costs, as companies may need to invest in expensive backup generation.4 Closing Africa's energy gap requires an estimated $190 billion annually.9
* **Transport and Logistics:** Poor and underdeveloped transportation networks (roads, rail, and ports) lead to **exceptionally high logistics costs and pose significant challenges for moving bulk raw materials and finished chemical products, especially hazardous materials**.4 Road transport can account for as much as 29% of the price of goods traded in Africa, compared to 7% for goods traded outside the continent.9 This not only increases costs but also leads to delays and potential product losses.4 The African Development Bank (AfDB) estimates that inadequate infrastructure decreases annual economic growth by two percentage points and reduces business productivity by up to 40%.12
* **Storage and Distribution:** There is often a **lack of specialized storage facilities** that meet international safety standards for chemicals, as well as inefficient distribution networks.3 This poses safety risks and limits the ability of the chemical industry to scale up operations efficiently.4 These infrastructural deficits create a "spatial penalty," making it difficult to establish competitive industries outside a few well-serviced urban enclaves, thus hindering broad-based and inclusive industrialization.

#### 3.2.3. Human Capital and Technological Capabilities

The shortage of skilled and experienced human capital is a pervasive challenge.10 This includes a lack of qualified chemical engineers, process operators, maintenance technicians, and managers with expertise in chemical plant operations.1 In South Africa, for instance, a significant skills gap exists, with only one engineer for every 2,114 citizens, compared to a ratio of 1:200 in countries like India or China.13 Educational and vocational training systems often suffer from a mismatch between curricula and the evolving needs of modern industry, including the digital skills required for 4IR technologies.10 This results in graduates who may not be adequately prepared for the technical and operational demands of a sophisticated chemical sector. Indigenous technological capabilities, including research and development (R&D) capacity, remain weak in many countries, limiting innovation and adaptation of technologies to local contexts.14 The "brain drain" phenomenon, where highly skilled professionals emigrate in search of better opportunities, further exacerbates this shortage.13 The skills gap is therefore not just quantitative but also qualitative, relating to the relevance of available skills to the demands of advanced manufacturing.

#### 3.2.4. Policy, Regulatory, and Institutional Frameworks

An unsupportive or unstable policy and institutional environment can severely undermine industrialization efforts. Political instability, corruption, and weak governance in some African nations create an unpredictable investment climate and deter long-term commitments.9 Outdated, inconsistent, or poorly enforced regulations related to business operations, environmental standards, and chemical management add to uncertainty and compliance costs.10 Bureaucratic hurdles can lead to significant delays in project approvals and licensing.10 A lack of coherent and consistently implemented industrial policies often means that strategic support for key sectors like chemicals is fragmented or insufficient.7 The legacy of past policy approaches, such as inefficiently managed import substitution or inadequately sequenced structural adjustment programs, has also contributed to the current state of industrial underdevelopment in some cases.15 Furthermore, weak intellectual property rights protection can discourage innovation and technology transfer.7 This policy and regulatory uncertainty acts as a significant "hidden tax" on industrial projects, increasing perceived risk. The absence of effective "soft infrastructure", such as robust institutions, clear and enforceable legal frameworks, and efficient public administration, is as critical a barrier as deficiencies in physical infrastructure.

#### 3.2.5. Sector-Specific Challenges (Feedstock, Market Access, Scale, Environmental Compliance)

The African chemical sector faces several challenges inherent to its nature and the continent's current developmental stage:

* **Feedstock Availability and Cost:** While Africa is rich in primary natural resources (minerals, oil, gas, biomass), the conversion of these resources into suitable, cost-effective chemical feedstocks locally can be problematic. In some instances, there is a paradoxical dependence on imported intermediate raw materials or processed feedstocks even when primary resources are available domestically, due to a lack of local processing capacity.13
* **Market Size and Integration:** Many individual African national markets are relatively small and fragmented, with low domestic purchasing power for sophisticated chemical products.7 While regional integration initiatives like the African Continental Free Trade Area (AfCFTA) aim to create larger markets, non-tariff barriers, poor interconnectivity, and inefficient customs processes continue to hinder intra-African trade.9
* **Economies of Scale:** Traditional chemical production often relies on achieving economies of scale through large, world-scale plants. However, the limited market sizes and high logistical costs of distributing products from a single large facility across vast and poorly connected regions make such investments risky and often unviable in the African context. This creates a "scale dilemma" where plants are either too large for the immediate market or too small to be conventionally economic.
* **Environmental Compliance and Management:** There is often a limited capacity within regulatory agencies to assess, monitor, and manage the environmental and health risks associated with chemical production and use.16 This can lead to concerns about the importation of hazardous or banned chemicals and weak enforcement of environmental standards.16 The sound management of chemicals and waste, including adherence to international conventions like the Globally Harmonized System (GHS) of Classification and Labelling of Chemicals, faces implementation challenges in downstream sectors dominated by small, informal businesses.16 Furthermore, water scarcity in certain African regions poses a direct threat to water-intensive chemical processes.13

The challenge of "appropriate scale" is particularly central to Africa's chemical sector development. The inability of many African markets to absorb the output of a world-scale conventional plant makes such investments highly speculative. This is where modular approaches, allowing for right-sized initial capacities with the potential for expansion, could offer a significant advantage.

Table 2*: Categorized Barriers to Industrialization in Africa's Chemical Sector*

|  |  |  |  |
| --- | --- | --- | --- |
| **Barrier Category** | **Specific Barrier** | **Description** | **Impact on Chemical Sector** |
| **Infrastructural** | Inadequate Energy Supply | Unreliable, insufficient, and often costly electricity and other energy sources. | Disrupts production, increases operational costs, makes energy-intensive processes unviable. |
|  | Poor Transportation Networks | Deficient roads, rail, ports, and pipelines. | Increases logistics costs for raw materials and products, limits market access, isolates production sites. |
|  | Limited Logistics and Storage | Lack of specialized storage for chemicals, inefficient customs and port handling. | Increases supply chain complexity and costs, risk of spoilage or damage. |
| **Financial** | Limited Access to Affordable Finance | High cost of capital, underdeveloped financial markets, risk aversion from lenders/investors. | Prevents investment in new plants and upgrades, particularly for capital-intensive chemical projects. |
|  | High Capital Costs for Conventional Plants | Traditional large-scale chemical plants require massive upfront investment. | Makes many projects unfeasible given market size and financial constraints. |
|  | Currency Volatility & Investment Risk | Unstable exchange rates and perceived high political/economic risks. | Deters foreign direct investment, increases cost of imported equipment and inputs. |
| **Human Capital** | Shortage of Skilled Technical Personnel | Lack of qualified chemical engineers, process operators, maintenance technicians, and managers. | Hampers plant operation, quality control, innovation, and adoption of new technologies. |
|  | Weaknesses in Education & TVET Systems | Insufficient focus on STEM, outdated curricula, lack of practical training facilities. | Fails to produce a workforce with relevant skills for the modern chemical industry. |
| **Policy & Institutional** | Unstable/Unsupportive Policy Environment | Frequent policy changes, lack of long-term industrial strategy, inadequate enforcement. | Creates uncertainty for investors, undermines long-term planning. |
|  | Regulatory Hurdles & Governance Issues | Complex and lengthy approval processes, corruption, weak rule of law. | Increases project costs and timelines, deters investment, can lead to unfair competition. |
|  | Weak Institutional Capacity | Limited ability of government agencies to effectively support and regulate industrial development. | Ineffective implementation of policies, poor monitoring, and lack of support services for industry. |
| **Market-Related** | Small and Fragmented Domestic Markets | Limited purchasing power and demand in individual national markets. | Makes it difficult to achieve economies of scale for large conventional plants. |
|  | Limited Regional and International Market Access | Trade barriers, lack of competitiveness, challenges in meeting international quality standards. | Restricts growth potential beyond small domestic markets. |
|  | Intense Global Competition | Competition from established, large-scale chemical producers in Asia, Europe, and North America. | Makes it difficult for nascent African industries to compete on price and scale. |
| **Technological** | Dependence on Imported Technology | Limited indigenous R&D, reliance on foreign technology suppliers and licensors. | Increases costs, limits adaptation to local conditions, hinders development of local innovation capacity. |
|  | *Limited Technology Transfer & Absorption* | *Difficulties in accessing, acquiring, effectively transferring, absorbing, and adapting appropriate and modern chemical production technologies.* |  |
|  | Limited Local R&D and Innovation | Insufficient investment in research and development, weak linkages between academia and industry. | Slows down technological upgrading, product development, and process optimization. |
|  | Challenges in Chemical Management & Safety | Lack of capacity to assess and monitor risks from chemicals, inadequate waste management, weak enforcement of safety standards. | Poses environmental and health risks, can lead to import of hazardous substances, increases operational liabilities. |

3.3. Evaluating the Potential of MCPs to Mitigate African Industrialization Barriers

This section critically assesses how the inherent characteristics and techno-economic advantages of modular chemical plants (MCPs), as detailed in Section 3.1, align with and potentially mitigate the multifaceted barriers to chemical sector industrialization in Africa, as identified in Section 3.2.

#### 3.3.1. Addressing Capital Investment and Financial Risk

A primary advantage of MCPs is their potential to significantly reduce upfront capital expenditure (CAPEX) compared to large-scale, stick-built facilities.11 This is achieved through efficiencies in workshop fabrication, reduced site preparation, and potentially lower civil engineering costs. For instance, some analyses suggest overall project cost reductions of up to 30% 11 and specific construction cost savings of 10-20%.29 This lower initial investment threshold can make chemical projects more accessible in Africa's capital-constrained environment, where securing large-scale financing is a major hurdle.9

The accelerated project timelines associated with MCPs, often reducing construction and commissioning from several years to potentially 18-24 months 11, lead to quicker revenue generation. This improves key financial metrics such as Net Present Value (NPV) and Internal Rate of Return (IRR), and shortens payback periods.30 In contexts with high perceived political and market risks, a shorter time to positive cash flow can significantly enhance project bankability and attractiveness to investors and lenders.

Furthermore, the concept of "numbering-up" or parallel modularity allows for a phased investment strategy.22 Instead of a single large, speculative investment, companies can start with a smaller modular unit to test the market and establish operations. Subsequent modules can be added incrementally as demand is proven and cash flow from initial units becomes available. This "grow-as-you-go" approach dramatically de-risks market entry and capacity expansion, aligning well with the uncertain and evolving nature of many African markets.22 This approach can also leverage "economies of numbers" or learning curves; as more identical modules are produced, the manufacturing cost per module tends to decrease due to accumulated experience and process optimization.28 While traditional plants benefit from "economies of scale" (lower unit cost at higher capacity), modularity offers a pathway to cost-effectiveness through standardized mass production of smaller units, potentially offsetting the loss of scale economies for certain capacity ranges.32 The argument that automation can diminish the labor cost advantages traditionally associated with large-scale plants further supports the economic rationale for smaller, automated modular units.32

#### 3.3.2. Enhancing Locational Flexibility and Overcoming Infrastructure Gaps

The physical characteristics of MCPs (smaller footprint, transportability, and reduced on-site construction requirements) offer significant advantages in overcoming Africa's infrastructural deficits.19

* **Siting near Resources or Markets:** MCPs can be sited closer to sources of raw materials (e.g., agricultural areas for biomass conversion, remote mineral deposits, stranded natural gas fields), thereby reducing the high costs and logistical complexities of transporting bulky or hazardous feedstocks over poor infrastructure.4 Alternatively, they can be located near end-users or industrial clusters, minimizing product distribution costs and improving market responsiveness. This capability can help unlock previously "stranded" resources that were uneconomical to exploit with large, centralized facilities.35
* **Reduced Reliance on Centralized Infrastructure:** The ability to deploy MCPs in remote or less-developed regions with limited access to extensive road, rail, or port facilities is a key benefit.20 While transportation of modules remains a challenge (discussed in 3.1.3), the overall demand on existing infrastructure for construction and operation can be less than for a massive stick-built plant.

**Localized Energy Solutions:** MCPs, particularly those with moderate energy demands or incorporating PI, can be more readily powered by localized or distributed renewable energy sources (e.g., solar PV, small-scale hydro, biomass-to-energy).22 This reduces dependence on often unreliable national grids and aligns with Africa's vast renewable energy potential. This potential for creating "industrial oases" or resource-based clusters in underserved regions can promote more equitable regional development, countering the "spatial penalty" that concentrates industry in a few prime locations.

#### 3.3.3.Impact on Speed-to-Market and Scalability for Nascent Markets

The rapid deployment capability of MCPs is a critical advantage for entering nascent or rapidly evolving African markets.11

* **Capturing First-Mover Advantages:** Shorter project cycles allow companies to establish a market presence quickly, potentially capturing first-mover advantages before larger, slower competitors can react.
* **Building Market Confidence:** In developing economies, a visibly operational plant can serve as a powerful catalyst, building confidence among local consumers, suppliers, and potential future investors. The "demonstration effect" of a quickly realized project can stimulate further economic activity and skills development in a way that protracted projects cannot.
* **Adaptive Scalability:** The "numbering-up" approach provides unparalleled scalability.22 Producers can start with an initial capacity tailored to current, often uncertain, market demand and then incrementally add identical modules as the market grows or new opportunities emerge. This mitigates the significant risks of overcapacity (leading to underutilized assets) or undercapacity (missing market opportunities) that are common with large, fixed-capacity plants. This allows for a "learning by doing" approach to market development, where expansion decisions are based on real operational data and market feedback, rather than solely on potentially unreliable forecasts in data-scarce African environments.

#### 3.3.4. Potential for Localized Value Addition and Resource Utilization

MCPs can be instrumental in facilitating the domestic processing of Africa's abundant natural resources, such as minerals, agricultural products, and oil & gas, into higher-value chemical intermediates and finished products.5

* **Import Substitution and Export Diversification:** Local production of essential chemicals (e.g., fertilizers for agriculture, water treatment chemicals, basic polymers) can reduce reliance on expensive imports, save foreign exchange, and improve national economic resilience.5 Furthermore, by adding value locally, MCPs can enable African countries to diversify their export baskets beyond raw commodities.
* **Specific Applications:**
  + **Fertilizers:** Small-scale modular ammonia and fertilizer plants, potentially utilizing green hydrogen from renewable sources, can supply local agricultural communities, reducing transport costs and improving access for smallholder farmers.36
  + **Gas Monetization:** Modular Gas-to-Liquids (GTL) or gas-to-chemicals plants can convert stranded or flared natural gas into valuable liquid fuels or chemical feedstocks, reducing environmental impact and creating economic value.22
  + **Mineral Beneficiation:** Modular units could be used for localized pre-processing or beneficiation of minerals, adding value before export or for local industrial use.
  + **Biomass Conversion:** Small-scale modular biorefineries can process agricultural residues or energy crops into biofuels and biochemicals, supporting rural development and energy diversification.22
* **Resilient Local Economies:** Localized value addition via MCPs can create more resilient local economies by reducing their dependence on volatile global commodity prices for raw material exports and the equally volatile prices for imported finished chemical products. This creates a "price scissors" buffer, enhancing economic stability.
* **Regional Value Chains:** MCPs could underpin the development of regional chemical value chains within Africa. Countries could specialize in producing specific chemicals based on their local resource endowments, using modular facilities, and then trade these intermediates or finished products within the AfCFTA framework, fostering intra-African trade and industrial integration.7

#### 3.3.5. Implications for Skills Development and Technology Transfer

The deployment of MCPs presents both challenges and opportunities for skills development and technology transfer in Africa.

* **Evolving Skill Requirements:** While some argue that standardized modules might simplify certain operational aspects, MCPs often incorporate advanced automation and process control systems, requiring a workforce skilled in their operation and maintenance.19 The integration of PI further necessitates specialized knowledge.22 This underscores the need for targeted training programs and curriculum updates in African technical institutions to align with the skills demanded by modern modular technologies.47
* **Opportunities for Phased Skills Development:** The modular nature itself might offer avenues for phased skills development. Initial projects could involve assembly and operation with significant vendor support, gradually transitioning to local teams taking on more complex maintenance and eventually even module adaptation or fabrication tasks.
* **Role of MCP Vendors:** Technology suppliers and engineering firms specializing in MCPs have a crucial role to play in providing comprehensive training, technical support, and fostering local partnerships.49 Effective technology transfer agreements should emphasize not just the hardware but also the "software" (operational know-how, design principles, maintenance protocols).
* **Decentralized Workforce Development:** The potential for dispersed MCPs means that skilled job opportunities could be created beyond traditional industrial hubs, potentially in rural or remote areas. However, this also poses a challenge for delivering adequate training and retaining skilled personnel in these locations.47
* **"Digestible" Technology Transfer:** Technology transfer associated with MCPs could be more effectively absorbed if it involves collaboration on module manufacturing or assembly over time, rather than solely relying on turnkey plant importation. This fosters deeper local learning, innovation capacity, and sustainable industrial capability building.

3.3.6. **Safety, Environmental, and Sustainability Considerations**

MCPs offer potential benefits in terms of safety and environmental performance, but also raise new considerations.

* **Enhanced Construction Safety:** As previously noted, off-site fabrication in controlled workshop environments significantly reduces construction-related accidents and hazards compared to traditional on-site work.19
* **Operational Safety:** Smaller inventories of hazardous materials at any single modular plant location can reduce the potential impact of an incident compared to a large-scale facility. For hazardous chemicals like chlorine or ammonia, producing them at or near the point of use via MCPs can drastically reduce transportation risks (e.g., road accidents, spills), which are particularly high in regions with poor transport infrastructure.19
* **Environmental Performance:**
  + MCPs can readily incorporate modern, cleaner, and more efficient PI technologies, leading to reduced emissions, lower energy consumption per unit of product, and minimized waste generation compared to older conventional plants.20
  + The smaller, distributed nature of MCPs might allow for more manageable and localized waste treatment solutions, potentially tailored to specific effluent streams.
* **Sustainability Alignment:** The ability to use local resources, reduce transport, improve energy efficiency, and potentially integrate with renewable energy sources aligns MCPs well with broader sustainable development goals.6
* **Regulatory Oversight for Dispersed Units:** A potential challenge is that the proliferation of many small, geographically dispersed MCPs, if not accompanied by robust environmental governance and monitoring systems, could lead to scattered pollution sources that are collectively difficult to manage, especially for regulatory agencies with limited capacity.16 Therefore, the environmental benefits of MCPs are contingent on effective regulatory frameworks and enforcement.

Table 3: *Matrix of Modular Chemical Plant Potentials vs. African Chemical Sector Industrialization Barriers*

|  |  |  |  |
| --- | --- | --- | --- |
| **Barrier Category** | **Key MCP Characteristic/Advantage** | **Potential of MCP to Mitigate Barrier** | **Mitigation Potential Score (H/M/L)** |
| **Economic & Financial** | Lower Upfront CAPEX | Makes projects more accessible with limited local capital; easier to secure smaller tranches of finance. Reduces overall financial risk. | H |
|  | Shorter Time-to-Market / Faster Revenue Generation | Improves NPV/IRR, shortens payback; reduces exposure to market & political volatility during long construction. | H |
|  | Phased Investment (Numbering-up) | Allows capacity to match market growth; reduces risk of over/under-capacity; cash flow from early units can fund expansion. | H |
|  | Economies of Numbers / Learning Curves | Potential for cost reduction through standardized module mass production, offsetting loss of scale economies. | M-H |
| **Infrastructural** | Locational Flexibility / Transportability | Enables siting near resources (reducing feedstock transport costs) or markets (reducing product distribution costs), even in remote areas. | H |
|  | Smaller Footprint | Reduced land requirement; easier site preparation. | M |
|  | Suitability for Distributed/Renewable Energy | Can be powered by localized renewable energy sources, reducing reliance on unreliable grids. | M-H |
|  | Reduced On-site Construction Complexity | Less demand on local heavy construction infrastructure and logistics. | M |
| **Human Capital & Technological** | Standardized Modules / Simpler O&M (for some configurations) | May reduce complexity for some operational tasks; potential for focused training on specific module types. | M |
|  | Vendor Training & Support | Opportunity for skills transfer from technology providers during installation and commissioning. | M |
|  | Potential for Local Adaptation/Learning | Phased local content development in module assembly/fabrication over time. | L-M |
| **Policy, Regulatory & Institutional** | Shorter Project Lifecycles (to first revenue) | Reduces exposure window to policy instability for initial investment. | M |
|  | Clearer Project Definition (due to upfront engineering) | May improve project bankability and interface with regulatory approval processes. | L-M |
| **Sector-Specific** | Scalability (Appropriate Scale) | Allows matching plant capacity to smaller/nascent African market demands, avoiding uneconomic large plants. | H |
|  | Point-of-Use Production (Hazardous Chemicals) | Reduces risks and costs of transporting hazardous materials like chlorine, ammonia. | H |
|  | Utilization of Stranded/Local Resources | Enables economic exploitation of dispersed resources (stranded gas, biomass, remote minerals). | H |
|  | Integration of Modern/Cleaner PI Technologies | Opportunity to build environmentally better plants from outset; smaller, contained waste streams. | M-H |
|  | Water Efficiency (with PI) | Some PI technologies can reduce water intensity, relevant for water-scarce regions. | L-M |

H = High, M = Medium, L = Low potential for mitigation.

This matrix (Table 3) illustrates a strong alignment between many advantages of MCPs and the key barriers hindering Africa's chemical sector. The most significant potential appears in addressing financial constraints, infrastructural limitations (particularly through locational flexibility), and the challenge of achieving appropriate scale for African markets.

#### 3.4. Techno-Economic Analyses and the Synthesis of Case Studies

3.4.1. *Review of TEA Frameworks for Modular Plants (NPV, ROI, Learning Curves, Economies of Numbers vs. Scale)*

The techno-economic assessment of MCPs requires frameworks that can adequately capture their unique characteristics compared to conventional plants. Standard metrics like Net Present Value (NPV) and Internal Rate of Return (ROI) remain crucial, but their calculation for MCPs must consider factors like phased investment, shorter project timelines leading to earlier cash flows, and the strategic flexibility offered by modularity, all of which can positively influence these indicators.30 For instance, a modular plant might present a more efficient concept for fast-growing products or those with volatile demands because the market impact during operation (flexibility) can outweigh the initial investment influence.30

A critical component in the TEA of MCPs is the incorporation of learning curves or economies of learning.28 As multiple identical or similar modules are manufactured, the cost per module is expected to decrease due to accumulated experience, improved labor efficiency, optimized supply chains, and refined manufacturing processes. This "learning effect" can be modeled using an experience curve, often expressed as a percentage cost reduction for each doubling of cumulative production (e.g., an 85% learning curve means the cost of the 2Nth unit is 85% of the cost of the Nth unit). Some analyses use parameters like a learning curve slope (α) and maximum achievable cost reduction (Rmax).28 This contrasts with the traditional "six-tenths rule" for economies of scale in stick-built plants, where cost scales with capacity to a power less than one. For modular plants, while individual modules might not show strong economies of scale, the overall project cost can benefit from the economies of numbers 32 – the cost savings derived from producing many standardized units. It is argued that automation in module fabrication can further diminish the labor cost advantages traditionally held by large-scale conventional plants, making economies of numbers more competitive.32

Conventional costing techniques need to be extended for modular units, often involving detailed cost estimation for prefabricated modules (including higher steel content and specialized transport) versus reduced on-site construction and installation costs.28 Some frameworks propose a "value density" concept, which considers product price, logistic costs, resource density, and desired production capacity to assess whether a centralized or distributed modular strategy is more appropriate for a given geographic area and resource.31 Low value density (e.g., high logistic costs for low-value feedstock) would favor distributed modular production.

The applicability of standard learning rates in the African context warrants careful consideration. Actual learning rates achieved in module manufacturing or assembly on the continent could vary significantly based on local skill levels, existing industrial capabilities, infrastructure quality, and the effectiveness of policy support and technology transfer mechanisms. Therefore, TEAs for MCPs in Africa should treat the learning rate as a critical sensitivity parameter. The "value density" concept, however, offers a potentially robust initial screening tool to identify high-potential applications for modularity across Africa's diverse resource and logistical landscapes.

3.4.2. *Analysis of Relevant Case Studies*

The literature provides several case studies and feasibility analyses of MCPs in chemical and related process industries, some of which are in Africa or analogous developing country contexts. These offer empirical insights into the practical application, costs, and benefits of modularity.

* **Chlor-Alkali:** A notable African example is the modular, skid-mounted chlor-alkali plant commissioned in Tanzania in 2018 by ThyssenKrupp. Designed to produce 15–45 tons/day of chlorine, its modules fit into 40-ft shipping containers. This plant, the first of its kind in sub-Saharan Africa, aims to provide local production for water treatment, reducing import reliance and transportation risks of chlorine. It exemplifies unitary modular manufacturing with potential for parallel numbering-up.22 While specific operational data is limited in the reviewed sources, its establishment signals interest in such solutions.
* **Gas-to-Liquids (GTL):** The Escravos GTL plant in Nigeria, with a capacity of 33,000 bbl/day, utilized extensive unitary modular construction (over 130 modules, some weighing over 2,600 tons) due to its remote mangrove swamp location. Although it faced significant cost escalations (final cost US$10 billion), modularity was deemed crucial for its development.22 More broadly, small-scale and micro-GTL plants are gaining attention for monetizing stranded or flared natural gas, a significant issue in many oil-producing developing countries. Studies suggest capacities from 7 bbl/d (micro GTL with CAPEX of $570k for the first unit, falling to $360k for the 100th unit due to learning effects) to 686 bbl/d, with potential for economic viability depending on oil prices and CAPEX reduction.44 A review by Höök et al. (2013) noted that while real-world large GTL projects often faced massive cost overruns (e.g., Escravos, Pearl GTL), small-scale GTL offers lower upfront costs and better cost control, making it attractive for associated gas.35
* **Fertilizers (Green Ammonia):** There is growing research on the techno-economic feasibility of small-scale, decentralized green ammonia production using renewable energy sources, particularly relevant for Sub-Saharan Africa to improve fertilizer access for agriculture. Smith and Torrente-Murciano (2021) evaluated the economic benefits of green ammonia from hydropower in Sierra Leone, estimating a 30-year NPV of ~$230M and ~165% ROI compared to importing fertilizers, saving at least $50M/year versus importing rice.37 Other studies analyze wind-powered green ammonia in Kansas (USA) with detailed financing options and community economic viability assessments, providing transferable methodologies.37 Case studies of larger renewable/low-carbon ammonia projects are emerging in developing countries like India (1 MMTPA renewable NH3), Chile (solar and wind-powered NH3), Morocco ($7B, 1 MMTPA green NH3), Brazil ($3B, 1 MMTPA blue NH3), and Nigeria ($3.5B, 1.66 MMTPA blue NH3 with CCS), indicating global interest and diverse technological pathways.40 The cost of green ammonia is currently higher ($794–$1,543/ton) than grey ammonia ($121–$518/ton), but is expected to fall, and can offer price stability.40
* **Mini-Refineries (Local Fuel Production):** Modular refineries, typically ranging from 1,000 to 30,000 bpd, are being developed in Nigeria to address domestic fuel shortages. These often start as simple Atmospheric Distillation Units (ADUs or "topping plants") in container-sized modules, with potential for upgrades. Advantages cited include lower investment, shorter payback periods (2-5 years compared to 5-10+ for conventional), and viability in remote locations.51 A financial analysis for a 10,000 bpd hydro-skimming modular refinery in Nigeria showed gross margins highly sensitive to crude oil price (e.g., 14.6% margin at $55/bbl, but -0.91% at $65/bbl) and refinery efficiency.51 A feasibility study for a micro-refinery in South Sudan highlighted the existing Bentiu modular refinery (5,000-10,000 bpd) and the potential for new modular units to process local crude, reducing import reliance, though facing challenges of political instability and infrastructure.45 Capital costs for mini-refineries are estimated between $20M-$50M.45
* **Water Treatment:** Tupelovox Pty. Ltd. in South Africa has implemented decentralized modular wastewater treatment and rainwater harvesting systems. One project for Vodacom featured a 1 megaliter storage capacity, harvesting 12 million L/yr of rainwater for non-potable reuse. Such systems offer affordable, adaptable solutions for smaller municipalities or industrial users, fostering economic development without reliance on extensions of large centralized sewer systems.22 Modular membrane-based water treatment systems are particularly recognized for their suitability in developing countries.34 Advantages include easy duplication and scale-up, a significantly smaller physical footprint than conventional plants (saving space and cost), lower energy consumption (as they often avoid phase-change processes), and the ability to serve small and distributed communities effectively.
* **Biomass Conversion:** TEAs for biomass-to-liquids (BTL) plants based on gasification (e.g., 2,000 metric tons/day of corn stover) have been conducted, comparing different gasifier technologies.46 Small-scale biomass gasification systems (e.g., 15 kWe) for electricity generation in Portugal and Brazil showed positive NPV (19-32k€), IRR (17-20%), and PBP (9-13 years), highlighting viability for decentralized energy in developing communities, though highly dependent on electricity sales prices.52
* **Pharmaceuticals/Active Pharmaceutical Ingredients (APIs):** Modular designs are increasingly considered for API manufacturing due to advantages in flexibility, speed, and quality control, which can be particularly beneficial for producing smaller batches of high-value products or responding to fluctuating demands, relevant for developing countries aiming to build pharmaceutical capacity.30 Continuous manufacturing, often suited to MCPI and modular designs, is seen as a way to improve efficiency in API synthesis.36
* **Specialty Chemicals:** The study by O'Connor et al. (2021), though not Africa-specific, provides a compelling economic case for MCPI in specialty chemicals production.26 Compared to a conventional stick-built (CSB) plant producing the same product at the same capacity, the MCPI approach demonstrated dramatically reduced CAPEX (attributed partly to smaller plant volume) and OPEX (due to automation of a previously labor-intensive batch process). The Net Present Value (NPV) for the MCPI case was nearly double that of the CSB case over a ten-year period, and the payback period for the CSB case was almost five times longer. This suggests significant economic advantages for high-value, lower-volume specialty chemical production where flexibility and speed can be paramount. Given Africa's growing demand for customized chemical solutions in various sectors (e.g., mining, agriculture, consumer goods) 22, modular specialty chemical plants could offer a route for local production, import substitution, and catering to niche market demands.

These case studies, while varied in scope and detail, collectively demonstrate growing interest and application of modular process plants in developing countries across diverse chemical sub-sectors. They highlight common themes: addressing local resource availability (stranded gas, biomass, renewables), meeting specific local demands (fuel, fertilizers, clean water), overcoming infrastructure limitations through decentralized deployment, and aiming for faster project execution with potentially lower initial capital outlays. However, economic viability often remains sensitive to feedstock and product prices, technology efficiency, and the scale of learning effects achieved.

3.4.3. *Quantitative Assessment of Potential Impact*

Quantifying the precise overall impact of MCPs on lowering barriers to African industrialization is challenging due to the heterogeneity of Africa's 54 nations, the diversity of its chemical sector needs, and the varied states of modular technology development and adoption. A comprehensive, continent-wide quantitative model is beyond the scope of this SLR. However, based on the techno-economic advantages and case study evidence, a qualitative and semi-quantitative assessment can be made regarding the *extent* to which modularization can help.

* **Capital Cost Reduction:** MCPs can potentially reduce upfront capital costs by 10-30% compared to conventional plants for similar effective capacities, especially when "economies of numbers" and learning effects are realized over a series of module deployments.11 For a hypothetical $100 million conventional small-to-medium chemical plant, this could mean savings of $10-30 million, significantly improving affordability in capital-scarce environments. The impact is **High**.
* **Schedule Compression:** Project timelines can be shortened by 25-50%.11 Reducing a 3-4 year project to 1.5-2.5 years accelerates revenue generation and reduces risk exposure. The impact is **High**.
* **Addressing Infrastructure Gaps:**
  + *Locational Flexibility:* Ability to site plants near resources or markets can drastically cut transport costs (which can be 29% of product price via road 9). This is a **High** impact for bulk-in/bulk-out processes or hazardous materials.
  + *Energy:* While MCPs still require energy, smaller, potentially PI-enhanced units may have lower specific energy consumption or be more amenable to local renewable sources, mitigating reliance on unreliable grids. This is a **Medium** impact, as energy source development is still key.
* **Market Access and Scale:** The ability to "right-size" capacity to nascent markets and scale incrementally is a **High** impact advantage, reducing the risk of failed large investments due to market misjudgment.
* **Skills and Technology:** MCPs do not inherently solve skills shortages but may offer more focused training opportunities on standardized modules. Effective technology transfer from vendors is crucial. The direct impact on this barrier is likely **Low to Medium** without accompanying human capital development strategies.
* **Policy and Regulatory Environment:** MCPs themselves do not change policy, but their characteristics (faster deployment, lower initial risk) might make them more resilient to policy volatility or more attractive for targeted policy support (e.g., for SMEs or decentralized development). Impact is **Indirect/Low**.

**Overall Extent:** Modular chemical plants have a **moderate to high potential** to lower several critical economic and infrastructural barriers to African chemical industrialization. Their most significant contributions are likely to be in:

1. **De-risking Investment:** Through lower initial CAPEX, phased deployment, and faster revenue generation.
2. **Enabling Localized Value Addition:** By allowing processing closer to resources or markets, especially for stranded assets or to meet specific local needs (e.g., fertilizers, water treatment).
3. **Improving Capital Efficiency for Small to Medium Markets:** By providing appropriately scaled technology that can grow with demand.

However, the extent of this impact is not uniform. It will be greater for:

* Chemicals with high transport cost sensitivity (either for feedstock or product).
* Processes amenable to significant process intensification.
* Regions with supportive policies for SMEs and decentralized industrialization.
* Projects where phased capacity addition aligns with market growth dynamics.

Modularization is less likely to be a panacea for deeply entrenched governance issues or severe human capital deficits on its own, but it can create new opportunities that, if coupled with appropriate enabling conditions, could significantly accelerate chemical sector development. A conservative estimate, based on potential CAPEX reductions and improved project viability, might suggest that MCPs could make an additional 10-20% of otherwise marginal chemical projects feasible in the medium term, and potentially accelerate the development of niche chemical value chains (e.g., bio-based chemicals, specialty fertilizers) that are ill-suited to mega-project approaches. The true quantitative impact will depend on the rate of technology adoption, the realization of learning economies in an African context, and the co-evolution of supportive policies and infrastructure.

3.5. Systems Analysis: Interplay of Factors and Dynamic Effects

The potential impact of modular chemical plants on African industrialization is not a simple linear relationship but involves a complex interplay of technological, economic, social, and policy factors. A systems perspective is necessary to understand these dynamics.

3.5.1. *Feedback Loops and Synergies*

The introduction of MCPs can trigger several feedback loops:

* **Positive Feedback Loops:**
  + *Investment-Skills-Market Loop:* Successful initial MCP projects (de-risked by modularity) can attract further investment. This creates demand for skilled labor, incentivizing training programs and skills development. As local production meets market needs reliably and cost-effectively, it can stimulate demand in downstream industries, creating larger markets that justify further MCP capacity expansion. The visibility of operational plants can build local confidence and catalyze ancillary service industries.
  + *Infrastructure-MCP Loop:* The deployment of MCPs in resource-rich remote areas might create the economic justification for targeted infrastructure development (e.g., improved access roads, local power solutions). Better infrastructure, in turn, makes further MCP deployment more feasible and cost-effective.
  + *Learning-Cost Reduction Loop:* As more modules are manufactured and deployed (potentially locally or regionally over time), learning effects can lead to reduced module costs and faster deployment, making subsequent MCP projects even more attractive.28 This is the core of "economies of numbers."
* **Potential Negative Feedback Loops (or Dampening Factors):**
  + *Skills Bottleneck:* Rapid MCP adoption without commensurate investment in specialized human capital development could lead to operational inefficiencies, higher maintenance costs, and project failures, thereby discrediting the technology and deterring future investment.
  + *Infrastructure Constraints:* If MCP deployment outpaces essential supporting infrastructure (reliable power for larger modules, adequate transport for module delivery or feedstock/product logistics), operational costs can escalate, and plant availability can suffer, negating some of modularity's benefits.
  + *Regulatory Lag:* If policy and regulatory frameworks do not adapt to support and govern decentralized, modular production effectively (e.g., streamlined permitting for smaller units, environmental monitoring for dispersed sites), bureaucratic delays and compliance uncertainties can stifle adoption.

Synergies can arise from combining MCPs with other strategic initiatives. For example, coupling MCP deployment with investments in renewable energy infrastructure can create green chemical value chains. Integrating MCP strategies with agricultural development programs (e.g., local fertilizer production) or public health initiatives (e.g., local production of water treatment chemicals or pharmaceutical ingredients) can amplify developmental impacts.

3.5.2. *Technology Adoption Dynamics in African Context*

The adoption of MCPs in Africa will likely follow patterns observed in technology diffusion theory, but with nuances specific to the continent's context.

* **Bass Diffusion Model Analogue:** The Bass model, often used to forecast new product adoption, considers innovators and imitators.53 In the context of MCPs, "innovators" might be pioneering companies (local or international) willing to take risks on first-of-a-kind modular projects in Africa, or specific governments championing the technology for strategic sectors. "Imitators" would follow once the benefits and viability are demonstrated by these early adopters. Patent citation data, as a proxy for technology diffusion (knowledge spillover), could potentially serve as a leading indicator for the uptake of specific modular chemical technologies, though this is more applicable to the underlying process technologies within the modules rather than modularity as a construction concept itself.53
* **Bandwagon Effects:** If early MCP projects in Africa demonstrate clear success (e.g., significant cost savings, faster completion, high profitability), this could trigger institutional and competitive bandwagon effects.54
  + *Institutional Bandwagon:* Other companies or even governments might adopt MCPs to appear modern, innovative, or to align with perceived best practices or donor preferences.
  + *Competitive Bandwagon:* Firms might adopt MCPs if they see competitors gaining an advantage (e.g., lower production costs, faster market entry) through their use. The characteristics of African "organizational collectivities" (e.g., risk aversion, access to information, strength of industry networks, government influence) will shape the occurrence, extent, and persistence of such bandwagons. Innovations with ambiguous returns, which could be the case for some MCP applications initially, can still diffuse via bandwagons if perceived momentum builds.54
* **Factors Influencing Adoption:** Key factors identified in general technology adoption literature that are highly relevant for MCPs in Africa include:
  + *Perceived Relative Advantage:* MCPs must offer clear benefits over traditional plants in terms of cost, speed, flexibility, or risk reduction relevant to the adopter's specific context.
  + *Compatibility:* Alignment with existing infrastructure (even if limited), skills, business practices, and regulatory frameworks.
  + *Complexity:* Ease of understanding, implementing, and operating the modular system. Highly complex systems may face slower adoption.
  + *Trialability:* The ability to pilot or adopt MCPs on a smaller, incremental scale (a key feature of "numbering-up") can significantly lower adoption barriers.
  + *Observability:* The visibility of successful MCP projects elsewhere in Africa or similar developing regions can accelerate adoption.
  + *Enabling Environment:* Government support, access to finance, availability of technical expertise, and supportive infrastructure are crucial enablers.

3.5.3. *Broader Economic Impacts (value Chain Development, Employment, Spillover Effects)*

The deployment of MCPs has the potential for broader economic impacts beyond the immediate project. While specific Computable General Equilibrium (CGE) models or detailed input-output analyses for MCPs in Africa are scarce in the reviewed literature, general principles can be inferred.

* **Value Chain Development:** MCPs can stimulate local and regional value chains.7
  + *Backward Linkages:* Demand for local inputs (e.g., certain raw materials if processed locally, construction materials, fabrication services if local capacity develops, maintenance services).
  + *Forward Linkages:* Supply of cost-effective and reliable chemical inputs to downstream industries (agriculture, manufacturing, pharmaceuticals, construction), potentially catalyzing their growth and competitiveness. For example, local fertilizer production can boost agricultural productivity, leading to growth in agro-processing.
  + *Example:* The GEMINI-E3 CGE model, though applied to Switzerland, includes a "Chemical" sector (No. 13 in its industrial classification), illustrating how such models can trace inter-sectoral linkages.56 CGE models are used for counterfactual analysis in energy and environmental economics, and can incorporate policy costs and embodied carbon emissions.57
* **Employment Generation:**
  + *Direct Employment:* Jobs in module fabrication (if localized), transportation, on-site assembly, operation, and maintenance of MCPs.2 While individual MCPs might be smaller, a strategy based on widespread deployment of numerous units could lead to significant cumulative employment.
  + *Indirect Employment:* Jobs created in upstream supplier industries and downstream user industries.
  + *Skill Upgradation:* Demand for new skill sets related to advanced manufacturing, automation, and process control can drive human capital development.
* **Technological Spillovers and Innovation:** The introduction and adaptation of MCP technology can lead to knowledge spillovers, fostering local innovation in related engineering, manufacturing, and service sectors.14 Local firms involved in MCP projects may develop new capabilities that can be applied elsewhere.
* **Regional Development:** Siting MCPs in underserved or remote regions can stimulate local economic activity, create jobs, and improve access to essential products, contributing to more balanced regional development.
* **Foreign Direct Investment (FDI) and Export Earnings:** Successful MCP deployment can attract FDI into the chemical sector. If local production achieves competitive cost and quality, it can lead to export earnings, particularly within the AfCFTA.

The overall economic impact will depend on the scale of MCP adoption, the degree of local content in module fabrication and services, the strength of linkages with the rest of the economy, and the supportive policy environment.

3.6. Risk Assessment and Mitigation Framework for MCP Deployment in Africa

Deploying MCPs in Africa, while offering potential benefits, also entails various risks that need systematic assessment and mitigation.

3.6.1. *Identifying Key Risks*

Based on the literature, key risks associated with MCP projects in the African context can be categorized as:

* **Technical Risks:**
  + *Performance of New/Unproven Modular Designs:* Some MCP technologies or specific process intensifications might be relatively new, carrying risks of underperformance, operational instability, or higher-than-expected maintenance.29
  + *Interface Mismanagement:* Challenges in ensuring proper connection and integration between modules on site.
  + *Feedstock Variability:* Inconsistent quality or supply of local feedstocks impacting plant performance.
  + *Utility Reliability:* Dependence on unreliable local power or water supply if dedicated utilities are not part of the modular package.
* **Economic and Financial Risks:**
  + *Cost Overruns:* Despite potential savings, risks of cost escalation in module fabrication, transportation, or site works remain, especially in unfamiliar operating environments.35
  + *Market Risks:* Uncertainty in demand, product prices, or competition from imports.30
  + *Currency Fluctuation and Inflation:* Impacting project costs and revenues.9
  + *Failure to Achieve Learning Economies:* If local conditions hinder the realization of cost reductions from repeated module production.
  + *Financing Risks:* Difficulty in securing follow-on funding for expansion phases if initial units underperform.42
* **Logistical and Supply Chain Risks:**
  + *Transportation Challenges:* Damage to modules during transit, delays due to poor infrastructure, customs hurdles.11
  + *Supply Chain Disruptions:* For specialized components, spare parts, or critical consumables.
  + *Site Access and Preparation Issues:* Difficult terrain, lack of heavy lifting equipment.
* **Political and Regulatory Risks:**
  + *Policy Instability:* Changes in industrial policy, investment incentives, or environmental regulations.9
  + *Permitting Delays:* Bureaucratic hurdles in obtaining necessary licenses and permits.
  + *Governance Issues:* Corruption or lack of transparency affecting project execution.9
* **Social and Human Capital Risks:**
  + *Skills Shortages:* Lack of trained personnel for operation, maintenance, and specialized fabrication/assembly tasks.10
  + *Community Acceptance:* Potential opposition if projects are perceived to have negative environmental or social impacts.
  + *Labor Issues:* Industrial relations, availability of skilled construction labor for site works.
* **Environmental Risks:**
  + *Waste Management for Dispersed Units:* Challenges in managing waste streams from multiple small plants if not properly planned.
  + *Environmental Compliance and Monitoring:* Ensuring adherence to standards across numerous sites with potentially limited regulatory capacity.16

3.6.2. *Risk Mitigation Strategies*

Effective risk mitigation is crucial for the success of MCP projects in Africa. Strategies should be proactive and integrated into the project lifecycle:

* **Technical Risk Mitigation:**
  + *Thorough Due Diligence on Technology:* Selecting proven modular designs and experienced vendors.
  + *Pilot Projects:* Conducting pilot projects for newer technologies or in new environments to validate performance and identify operational challenges.
  + *Standardization and Quality Control:* Ensuring high-quality fabrication in workshops and robust interface engineering.
  + *Robust O&M Planning:* Developing comprehensive maintenance schedules and ensuring availability of spare parts and skilled technicians.
* **Economic and Financial Risk Mitigation:**
  + *Detailed Feasibility Studies and TEAs:* Incorporating realistic local cost data, conservative assumptions, and extensive sensitivity analysis.
  + *Phased Investment:* Utilizing the "numbering-up" approach to reduce initial capital exposure and scale with market demand.22
  + *Securing Offtake Agreements:* Guaranteeing markets for products can improve bankability.
  + *Financial Hedging:* For currency and commodity price risks, where feasible.
  + *Public-Private Partnerships (PPPs):* To share risks and leverage public sector support for infrastructure or policy stability.42
  + *Diversified Funding Sources:* Combining local and international finance, development finance institutions (DFIs).
* **Logistical and Supply Chain Risk Mitigation:**
  + *Early Route Surveys and Logistics Planning:* Detailed assessment of transport routes and infrastructure constraints.60
  + *Modular Design for Transport:* Optimizing module size and weight for existing infrastructure.
  + *Experienced Logistics Partners:* Engaging specialized firms with experience in heavy/oversized cargo and African logistics.
  + *Local Sourcing/Fabrication Development:* Gradually developing local capacity for some components or module assembly to reduce import reliance.
* **Political and Regulatory Risk Mitigation:**
  + *Stakeholder Engagement:* Early and continuous engagement with government agencies, local communities, and other stakeholders.
  + *Political Risk Insurance:* Where available and cost-effective.
  + *Understanding Local Context:* Deep understanding of the local political, legal, and regulatory landscape.
  + *Advocacy for Stable Policies:* Working with industry associations and government to promote predictable and supportive regulatory frameworks.
* **Social and Human Capital Risk Mitigation:**
  + *Targeted Training Programs:* Collaborating with local technical institutions to develop curricula and training programs for MCP operation and maintenance.47
  + *Community Development Initiatives:* Ensuring projects deliver tangible benefits to local communities.
  + *Phased Introduction of Technology:* Allowing time for local skills to develop alongside project expansion.
* **Environmental Risk Mitigation:**
  + *Comprehensive EIAs:* Conducting thorough Environmental Impact Assessments tailored to local ecosystems.
  + *Adoption of Cleaner Technologies:* Utilizing PI and BAT (Best Available Techniques) in modular designs.
  + *Robust Waste Management Plans:* For both construction and operational phases, considering the distributed nature of plants.
  + *Transparent Monitoring and Reporting:*

A combination of risk transfer (e.g., insurance), risk mitigation (proactive measures), risk avoidance (changing plans to eliminate high risks), and carefully considered risk acceptance is often the most effective approach.42

3.7. Policy and Strategic Framework for Promoting MCPs in Africa

Realizing the potential of MCPs to contribute to African industrialization requires a conducive and proactive policy and strategic framework. This framework should address enabling conditions, human capital, infrastructure, technology transfer, and regional cooperation.

3.7.1. *Enabling Policies and Regulatory Best Practices*

Governments play a pivotal role in creating an environment where MCPs can thrive:

* **Supportive Industrial Policies:** National industrial policies should explicitly recognize and support innovative approaches like modular manufacturing, particularly for strategic sectors like chemicals. This includes setting clear targets and providing strategic direction.7 Technology road mapping, adapted for developing country contexts (considering multilevel perspectives, transition management, and leapfrogging strategies), can be a valuable tool for planning the adoption and diffusion of MCP technologies.66
* **Streamlined and Adapted Regulatory Frameworks:**
  + *Permitting and Licensing:* Regulatory bodies should develop streamlined, efficient, and potentially adapted permitting and licensing processes for smaller, standardized modular plants, reducing bureaucratic delays that disproportionately affect smaller investments.67 This might involve creating specific regulatory pathways for modular facilities.
  + *Environmental Regulations:* While maintaining high environmental standards, regulations should be clear, consistently enforced, and adaptable to the distributed nature of some MCP deployments.
  + *Safety Standards:* Clear safety codes and standards for the design, fabrication, transportation, installation, and operation of MCPs are essential.
* **Investment Incentives:** Targeted incentives can encourage investment in MCPs. These could include:
  + *Fiscal Incentives:* Tax breaks, accelerated depreciation, or duty exemptions for imported modules or critical components, especially in the initial phases of technology adoption.9
  + *Financial Support:* Access to dedicated financing windows, loan guarantees, or co-investment funds for MCP projects, particularly for local SMEs.9
  + *Support for R&D and Innovation:* Funding for local adaptation of modular designs or development of PI technologies suitable for modularization.
* **Intellectual Property (IP) Protection:** Strong and enforceable IP rights are necessary to encourage technology transfer and local innovation related to MCPs.7
* **Development of Special Economic Zones (SEZs):** SEZs can provide enabling infrastructure, streamlined regulations, and incentives, making them attractive locations for pioneering MCP projects.7 UNIDO has experience supporting SEZ development in Africa.59

3.7.2. *Human Capital Development Strategies*

Addressing the skills gap is critical for the successful adoption, operation, and maintenance of MCPs:

* **Curriculum Development and Reform:** Technical and vocational education and training (TVET) institutions and universities need to update their curricula to include modern process technologies, PI, automation, and skills relevant to modular plant O&M.47 This requires close collaboration between industry and educational institutions. The CDIO (Conceive-Design-Implement-Operate) initiative offers a framework for engineering education reform that could be relevant.48
* **Specialized Training Centers:** Establishment of specialized training centers or programs focused on modular technologies and specific chemical processes.
* **Public-Private Partnerships for Skills Development:** Collaboration between MCP vendors, industry players, and educational institutions to deliver targeted training and apprenticeships.
* **Upskilling and Reskilling Existing Workforce:** Programs to upgrade the skills of the current industrial workforce to adapt to new technologies.
* **Attracting and Retaining Talent:** Creating attractive career pathways and incentives to retain skilled engineers and technicians domestically.

3.7.3. *Infrastructure Development and Logistics Planning*

While MCPs can offer some relief from infrastructure constraints, targeted infrastructure development remains crucial:

* **Integrated Infrastructure Planning:** MCP deployment strategies should be integrated with national and regional infrastructure development plans, particularly for transport (roads, rail, ports suitable for module transport) and energy (reliable grid connections or support for off-grid renewable solutions).60
* **Logistics Capabilities:** Investment in developing local logistics capabilities, including heavy lifting and specialized transport services.
* **Digital Infrastructure:** Reliable communication infrastructure is important for remote monitoring and control of dispersed modular units.

3.7.4. *Fostering Technology Transfer and Local Innovation*

Maximizing the benefits of MCPs requires effective technology transfer and the development of local innovative capacities:

* **Strategic Partnerships with Technology Providers:** Encouraging joint ventures and partnerships with experienced MCP vendors that include clear provisions for technology transfer, training, and local content development.49
* **Support for Local Adaptation and R&D:** Providing funding and institutional support for R&D aimed at adapting modular designs to local conditions, feedstocks, and market needs.
* **Developing Local Manufacturing Capabilities:** Over the long term, fostering local capabilities in module fabrication and assembly can create significant value and employment. This might start with simpler balance-of-plant modules and gradually move to more complex process modules.
* **Knowledge Sharing Platforms:** Creating platforms for sharing best practices, lessons learned, and technical knowledge related to MCP deployment within and between African countries.

3.7.5. *Role of Regional Cooperation and Institutions*

Regional cooperation and strong institutional support can significantly accelerate the adoption and impact of MCPs:

* **African Continental Free Trade Area (AfCFTA):** The AfCFTA can create larger, more integrated markets, making MCP investments more attractive by enabling access to regional demand and facilitating trade in modularly produced chemicals and modules themselves.9 Harmonization of standards and regulations under AfCFTA is key.
* **Regional Economic Communities (RECs):** RECs can play a role in coordinating cross-border infrastructure projects, harmonizing policies, and promoting regional value chains based on modular chemical production.
* **Development Finance Institutions (DFIs):** Institutions like the African Development Bank (AfDB), World Bank, and others can provide critical financing, technical assistance, and risk mitigation instruments for MCP projects.58
* **International Organizations (e.g., UNIDO, UNECA):** These organizations can provide policy advice, capacity building, support for technology transfer, and facilitate knowledge sharing on modular technologies and sustainable industrial development.6 UNIDO, for example, has a focus on sustainable industrial development, clean energy, and sustainable supply chains, all relevant to MCP deployment.6

A holistic and coordinated approach involving governments, the private sector, educational institutions, and regional/international partners is essential to create a supportive ecosystem for leveraging modular chemical plant technology for Africa's industrial transformation.

**4.0. Conclusion**

4.1. Synthesis of Findings and Answer to Research Questions

This systematic literature review set out to determine if modular chemical plants (MCPs) can lower the barriers to African industrialization, with a specific focus on the continent's chemical sector, and if so, to what extent. The synthesized evidence from peer-reviewed literature and authoritative reports indicates an affirmative answer to the primary research question: **Modular chemical plants possess significant potential to lower several critical barriers impeding the industrialization of Africa's chemical sector.**

MCPs, characterized by off-site fabrication of skid-mounted or containerized units, offer distinct techno-economic advantages that align well with Africa's challenging operational and investment landscape. Key findings indicate that MCPs can:

* **Mitigate Financial Barriers:** By offering lower upfront capital expenditure, faster project execution leading to earlier revenue generation, and the possibility of phased investment through "numbering-up," MCPs can de-risk projects and improve their bankability in capital-scarce African economies. The potential to achieve "economies of numbers" through standardized module production offers an alternative pathway to cost-effectiveness.
* **Address Infrastructural Deficits:** Their smaller footprint, transportability, and reduced on-site construction complexity allow for greater locational flexibility. This enables siting near remote raw material sources or dispersed end-user markets, reducing reliance on extensive, often inadequate, centralized transport and energy infrastructure.
* **Navigate Market Uncertainties:** The scalability of MCPs allows production capacity to be matched more closely with nascent or uncertain market demands, avoiding the risks of large, underutilized conventional plants. Speed-to-market also allows for quicker responses to emerging opportunities.
* **Facilitate Localized Value Addition:** MCPs can enable the processing of Africa's natural resources closer to source, fostering import substitution, export diversification, and the development of local and regional value chains.
* **Enhance Safety and Potentially Sustainability:** Controlled factory fabrication improves construction safety, and point-of-use production of hazardous chemicals can reduce transportation risks. Integration with process intensification (PI) can lead to smaller, more efficient, and potentially cleaner processes.

Regarding the follow-up question *“To what extent can modularization help African industrialization?”*, the analysis suggests a **moderate to high potential impact**, contingent on several factors. The extent is not uniform and will vary based on:

* **The specific chemical sub-sector:** MCPs may be more immediately impactful for specialty chemicals, agrochemicals (like small-scale fertilizer plants), water treatment chemicals, and monetizing stranded gas or biomass resources, where smaller scales and flexibility are advantageous. For very large-scale bulk petrochemicals, conventional plants might still hold scale advantages, though unitary modular construction can still offer benefits.
* **The specific African context:** Countries with proactive industrial policies, improving governance, targeted skills development programs, and a willingness to embrace innovative technologies will be better positioned to leverage MCPs.
* **The maturity and cost-competitiveness of specific modular technologies:** As MCP and MCPI technologies continue to evolve and their costs decrease (particularly through learning effects), their applicability will broaden.
* **The presence of enabling conditions:** Successful widespread adoption requires supportive policies, access to appropriate finance, development of relevant human capital, and strategic infrastructure planning.

Quantitatively, while precise continent-wide figures are elusive, case studies and techno-economic analyses suggest potential CAPEX reductions of 10-30% and schedule compressions of 25-50% for specific projects. This can make a significant number of previously marginal or unviable chemical projects feasible. The ability to right-size plants to local demand can unlock numerous smaller opportunities that would be overlooked by traditional mega-project approaches.

4.2. Overall Assessment

Modularization is not a panacea for all challenges facing African industrialization. It cannot, in isolation, resolve deep-seated issues of governance, macroeconomic instability, or fundamental gaps in education. However, it represents a potentially transformative technological and strategic tool that can significantly lower the entry barriers and alter the risk-reward profile for chemical industry investments in Africa.

MCPs offer a pathway to a more decentralized, flexible, and potentially more resilient chemical manufacturing ecosystem. This approach can empower local entrepreneurship, facilitate the development of SMEs in the chemical sector, and promote more inclusive industrial growth by enabling value addition in regions previously bypassed by industrial development. The synergy with process intensification (MCPI) further enhances this potential, paving the way for modern, efficient, and more sustainable chemical production.

The successful adoption of MCPs could allow African nations to leapfrog traditional phases of industrial development22, establishing a 21st-century chemical industry grounded in agility, resource efficiency, and adaptability. This requires a paradigm shift from thinking solely in terms of large, centralized mega-projects towards embracing a portfolio of appropriately scaled and strategically located modular facilities.

4.3. Limitations of the Study

This Systematic Literature Review, while comprehensive, has certain limitations:

* **Publication Bias:** The review relies on published literature, which may be subject to publication bias (e.g., a tendency to publish positive results or successful case studies more readily than failures).
* **Data Scarcity for Africa-Specific MCPs:** While efforts were made to find Africa-specific data, detailed techno-economic analyses and operational case studies of MCPs within the African chemical sector are still relatively scarce. Much of the analysis relies on extrapolating from developing country contexts or general modular principles.
* **Heterogeneity of Data:** The techno-economic data extracted from various sources often had different assumptions, scopes, and levels of detail, making direct quantitative comparisons and meta-analysis challenging.
* **Dynamic Nature of Technology and Markets:** Modular technology and African markets are continuously evolving. This review provides a snapshot based on currently available information.
* **Focus on Technical and Economic Aspects:** While policy and social aspects were considered, the primary lens was chemical engineering-based techno-economic analysis. A deeper socio-political analysis would require a different disciplinary focus.

4.4. Recommendations for Future Research

The findings of this SLR highlight several areas requiring further investigation:

1. **Africa-Specific Techno-Economic Analyses:** Conduct detailed TEAs for specific MCP applications (e.g., modular fertilizer plants using local phosphate rock and renewable energy, small-scale GTL from flared gas, modular API production) tailored to the economic, infrastructural, and resource contexts of individual African countries or regions.
2. **Pilot Projects and Demonstration Plants:** Support the establishment of MCP pilot and demonstration projects in Africa to gather empirical data on performance, costs, operational challenges, and local adaptability.
3. **Learning Curve Dynamics in Africa:** Research the actual learning rates achievable in module fabrication, assembly, and operation within African industrial ecosystems, and the factors influencing them.
4. **Supply Chain Development for MCPs in Africa:** Investigate the potential for developing local and regional supply chains for MCP components, engineering services, and O&M support.
5. **Regulatory Impact Assessments:** Analyze the impact of different policy incentives and regulatory frameworks on the adoption and success of MCPs in African countries.
6. **Human Capital Development Models:** Develop and evaluate effective models for training and skills development to create a workforce capable of designing, operating, and maintaining MCPs in Africa.
7. **Environmental Life Cycle Assessments (LCAs):** Conduct comprehensive LCAs for MCPs in specific African applications to quantify their environmental footprint compared to conventional alternatives and imports.
8. **Socio-Economic Impact Assessment:** Broader studies on the socio-economic impacts of MCP deployment, including employment generation (direct and indirect), community development, and contributions to achieving SDGs.

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