VACCINE INSIGHTS

SUSTAINABILITY IN VACCINE DEVELOPMENT AND PRODUCTION

SPOTLIGHT

REVIEW

Building long-term vaccine manufacturing capacity for the world: a framework for sustainable development in LMICs

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The recent global pandemic has put in the spotlight the urgent need for low- and middle-income countries (LMICs) to develop sustainable vaccine manufacturing capacity to ensure equitable access to life-saving vaccines in future health crises. This paper reviews current practices and highlights an informed framework for building long-term vaccine manufacturing capacity in LMICs, emphasizing the importance of local, regional, and global cooperation. Key recommendations include strengthening domestic leadership and technical training, creating a workable locally achievable regulatory environment, fostering public–private partnerships. Additionally, the framework outlines a phased approach to capacity building, with immediate priorities focused on infrastructure and technology transfer, followed by medium-term goals of scaling production and ensuring self-sufficiency. The paper also proposes metrics for success, including the number of doses produced locally, the percentage of vaccines procured from LMIC manufacturers, and the speed of vaccine development during outbreaks. The framework aims to empower LMICs to lead in vaccine production, reducing dependency on high-income countries and promoting a more equitable, resilient global health system.

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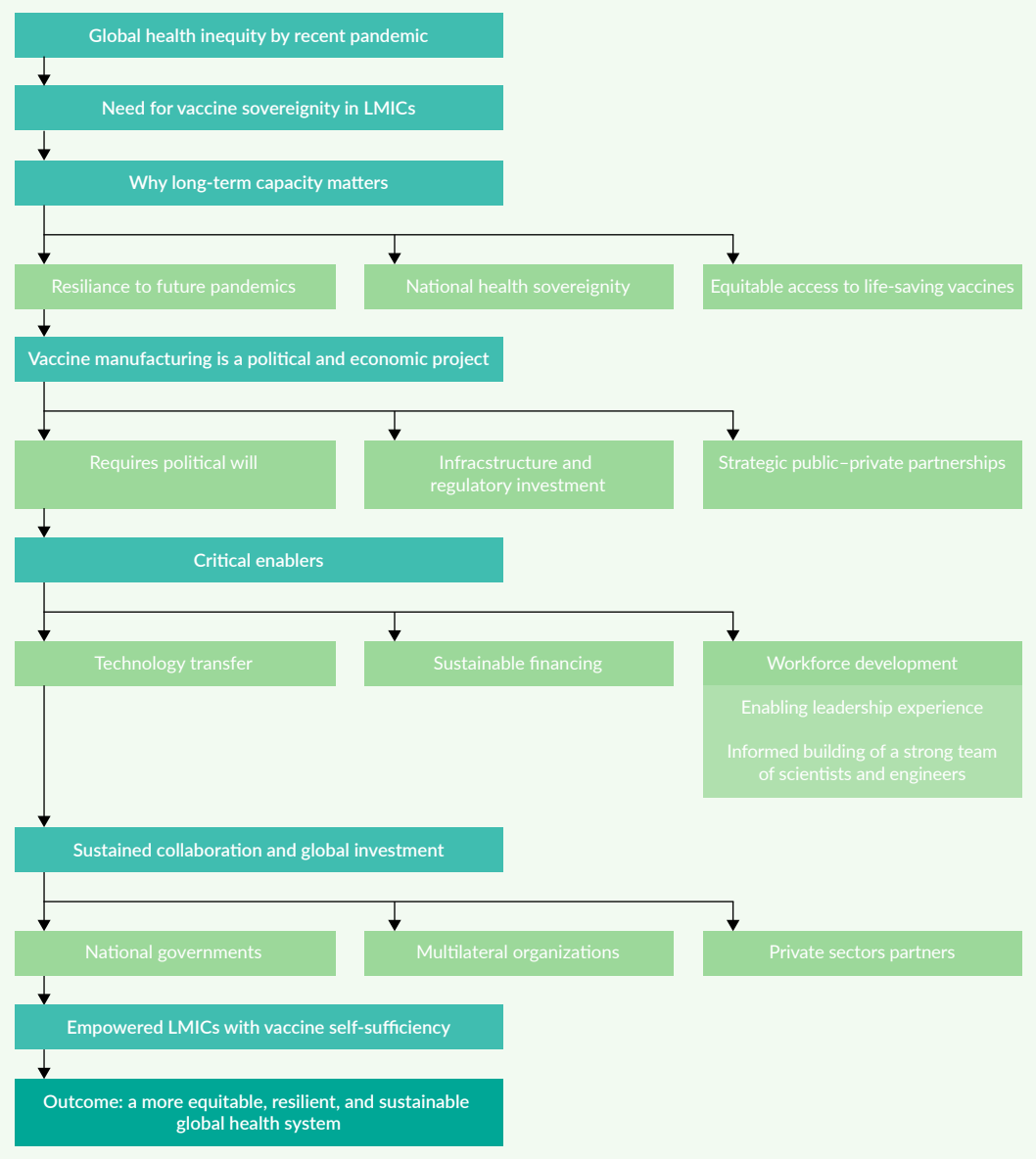
INTRODUCTION

Importance of global vaccine equity and the need for distributed manufacturing

Global vaccine equity refers to the fair and equitable distribution of vaccines across all nations, regardless of their economic status. This principle is vital not only from an ethical standpoint but also for effective pandemic control and global health security. During the COVID-19 pandemic, disparities in vaccine access led to prolonged outbreaks in low- and middle-income countries (LMICs), allowing viral mutations



Graphical abstract. Powering global health from the ground up: a visual journey through the pillars of sustainable vaccine manufacturing in LMICs.

to occur and increasing the risk of global transmission. As of late 2021, for example, more than 70% of people in high-income countries had received at least one vaccine dose, compared to just 4% in low-income countries [1,2]. However, to better understand the needs for vaccine supply and production it is worthwhile reviewing the definition of what is meant by low or middle-income countries. According to the World Bank, there has been some significant shifts in reclassification of certain countries/regions since the late 1980s, with some regions (e.g., South Asia) reducing their share of low-income to only 13%. [3]. It is therefore difficult to consider that the same policies and recommendations would be applicable to all countries that may fall under one or other categories. But one certainty is in that irrespective of location or wealth, there is a global need for vaccines either during a crisis (pandemic or endemic) or as insurance against such surges.

The COVID-19 pandemic exposed critical vulnerabilities in the global vaccine

manufacturing landscape, particularly in low- and middle-income countries (LMICs), where limited infrastructure, supply chain dependencies, and insufficient policy support hindered timely access to life-saving vaccines [2,4]. In response, there has been growing momentum to localize vaccine production in LMICs to improve regional self-sufficiency, reduce reliance on external suppliers, and enhance pandemic preparedness. This manuscript explores the strategic considerations for building long-term, sustainable vaccine manufacturing capacity in LMICs, including the optimal number, size, and type of facilities, as well as the local, continental, and global policy interventions needed to support these efforts.

While the primary focus of this study is on low- and middle-income countries (LMICs), it is essential to acknowledge that high-income countries (HICs) also faced notable constraints in vaccine manufacturing during the COVID-19 pandemic. Despite their advanced healthcare infrastructure and financial resources, several HICs, including Canada, Australia, Japan, and the Netherlands, lacked sufficient domestic vaccine production capacity and were consequently dependent on international supply chains to secure vaccine doses [5].

Canada, for example, had limited domestic biomanufacturing capabilities at the onset of the pandemic and was compelled to rely on imports from countries such as India and the United States to meet its vaccination needs [5,6]. Similarly, Australia initially depended on imported vaccines before scaling up local production of the AstraZeneca vaccine, underscoring the vulnerability of even well-resourced nations to global supply chain disruptions [6,7]. Japan and the Netherlands also experienced delays in vaccine rollout due to their reliance on external manufacturing sources [8].

These challenges highlight a broader systemic issue: the global concentration of vaccine manufacturing in a limited number of countries created bottlenecks that affected both LMICs and HICs. The World Health Organization (WHO) has emphasized that equitable access to vaccines requires not only dose sharing but also the decentralization and expansion of manufacturing capabilities worldwide [6]. Strengthening regional production hubs and investing in end-to-end vaccine development infrastructure are now recognized as critical strategies to enhance global pandemic preparedness and resilience [5].

This reliance exposed vulnerabilities in global supply chains and highlighted the need for broader investment in manufacturing infrastructure, technology transfer, and policy coordination across all income levels. The pandemic demonstrated that vaccine equity and preparedness are global issues, not confined to LMICs alone. Strengthening regional and global collaboration, including among HICs, will be essential to ensure a resilient and inclusive vaccine manufacturing ecosystem for future health emergencies [7,9].

Challenges in vaccination in LMICs

LMICs entered the pandemic with limited healthcare infrastructure, high dependency on imports, and insufficient manufacturing capabilities. The resulting supply chain disruptions led to critical shortages of medicines and equipment, particularly in regions like sub-Saharan Africa [10]. The closure of borders, reduced air traffic, and delays in international aid further deepened the crisis.

The growing focus on localized vaccine manufacturing in low- and middle-income countries (LMICs) is seen as a vital strategy to enhance global health equity, lessen reliance on high-income nations, and improve regional preparedness for future pandemics. By producing vaccines locally, LMICs can reduce vulnerabilities associated with global supply chain disruptions, ensure more equal access to essential vaccines, and strengthen healthcare systems. Additionally, local manufacturing can

drive economic growth, generate employment, and alleviate the financial burden of depending on foreign suppliers. However, despite these significant advantages, several key challenges hinder the effective scaling of vaccine production in these regions [11].

Skilled workforce and training gaps

A central challenge in establishing vaccine manufacturing capabilities in LMICs is the lack of a sufficiently skilled workforce. The production of vaccines is a complex, technology-driven process that requires expertise in various fields such as biotechnology, microbiology, engineering, and quality assurance. Strong leadership capability and specialized knowledge and skills required to run vaccine production facilities are often in short supply in many LMICs due to deficiencies in educational infrastructure, limited access to advanced training, and the outflow of talent to higher-paying positions in developed countries. As a result, these countries struggle to develop a competent workforce capable of supporting the advanced manufacturing processes needed for large-scale vaccine production, this includes gaps in technical expertise, quality assurance, and bioprocess engineering, skills that are essential for operating and scaling vaccine production facilities. While not the only challenge, we maintain that workforce limitations are a critical constraint, particularly when combined with limited access to advanced training programs and retention issues due to brain drain [12,13]. According to a study by the WHO, fewer than 30% of the national regulatory authorities (NRAs) in LMICs have the necessary capacity to regulate the production of medical products, including vaccines, effectively [2]. This further exacerbates the situation, as a lack of skilled personnel delays production timelines, affects product quality, and hampers national vaccine manufacturing initiatives [5,14].

Regulatory hurdles

Regulatory challenges present another significant barrier to the scaling of vaccine manufacturing in LMICs. Several countries in these regions lack well-established and fully functional regulatory systems, which are necessary to ensure the safety, efficacy, and quality of vaccines. The WHO's prequalification process, which is required for vaccines to be approved for international distribution, can be lengthy, costly, and difficult for LMICs to navigate. A lack of harmonized regulatory standards between countries further complicates vaccine approval, particularly when vaccines must undergo multiple evaluations across different national regulatory bodies. For instance, although there has been progress in some regions, such as the African Union's efforts to enhance local vaccine production capabilities, only a small proportion of African countries have regulatory systems that meet the WHO's standards for vaccine quality assurance. This delay in regulatory capacity often leads to the slow approval of vaccines and can prevent LMICs from benefiting from the global vaccine market or protecting their populations from vaccine-preventable diseases in a timely manner. Regulatory capacity refers not only to the existence of national regulatory authorities (NRAs) but also to their ability to meet international standards for vaccine approval, quality control, and pharmacovigilance. In many LMICs, NRAs are under-resourced or lack WHO maturity level 3 or 4 status, which can delay local production and international distribution. Strengthening regulatory systems is therefore essential for enabling timely and safe vaccine manufacturing, strengthening the capacity of regulatory authorities through international collaboration and training is essential to overcoming these hurdles and ensuring that locally produced vaccines meet global standards [15–18].

Market demand predictability and procurement assurance

A third major challenge is the unpredictable nature of vaccine demand and the uncertainty surrounding procurement processes. Without long-term, reliable procurement agreements and purchasing commitments, local manufacturers face significant risks. For instance, if manufacturers are unable to predict the demand for vaccines with accuracy, they may face either overproduction or shortages. This can lead to inefficiencies, wasted resources, and financial losses, which deter private investment in vaccine manufacturing in LMICs. Additionally, without strong procurement guarantees, manufacturers may be hesitant to invest in infrastructure and technology upgrades necessary for scaling up production.

The unpredictability of vaccine demand is further compounded by the fact that many LMICs rely on international organizations such as Gavi and UNICEF for vaccine procurement and distribution. While these organizations play a critical role in ensuring global access to vaccines, their funding and distribution strategies may not always align with the specific needs or timelines of local manufacturers. In some cases, the delay in procurement decisions and the lack of clear market signals have left manufacturers with unsold vaccines, undermining their economic sustainability. Securing long-term commitments and creating predictable, transparent vaccine markets is essential to building local manufacturing capacity and encouraging investment in this sector [14,19].

Cost and financing constraints

Finally, one of the most significant barriers to establishing and scaling up vaccine manufacturing in LMICs is the high cost of building and operating production facilities. The initial capital investment required for establishing a vaccine manufacturing plant, including the costs of purchasing equipment, facilities, and raw materials, is substantial. Moreover, ongoing operational costs, including those related to quality control, workforce maintenance, and raw material sourcing, are also considerable. Many LMICs struggle to secure the necessary financing to cover these costs due to limited access to capital markets, donor fatigue, and the absence of sustained financial support from international partners.

A recent study estimates that LMICs face a funding gap of US$ 38.4 billion for vaccine acquisition and delivery between 2011 and 2030. This financial shortfall highlights the challenge of ensuring sustainable vaccine production and delivery in low-income countries. Innovative financing models, such as public-private partnerships, foreign direct investment, and international grants, will be key to addressing this gap and enabling LMICs to build and sustain their own vaccine manufacturing capabilities. Additionally, financing efforts should focus on reducing the risk for private sector players to encourage investment in local manufacturing, which will lead to more affordable vaccines and greater resilience against future health crises [19].

While the development of localized vaccine manufacturing in LMICs is crucial for improving global health outcomes, significant challenges remain. Overcoming these barriers requires a multi-faceted approach, including investments in education and workforce development, strengthening regulatory systems, ensuring predictable market demand, and securing sustainable financing. Only by addressing these interconnected challenges can LMICs develop the capacity to produce vaccines locally, enhance their pandemic preparedness, and reduce their dependence on high-income countries for essential healthcare supplies.

Vaccine inequity has several far-reaching consequences

- Prolonged pandemics: when large populations remain unvaccinated, the virus continues to spread and mutate, undermining global health gains [20]
- Economic impacts: global economic recovery is tied to health security. The International Monetary Fund (IMF) estimated that vaccine inequity could cost the global economy over US$ 9 trillion [21]
- Erosion of trust: Inequitable access can lead to distrust in international institutions and fuel vaccine hesitancy within underserved communities [22]

The case for distributed manufacturing

To address the root causes of vaccine inequity, distributed vaccine manufacturing, producing vaccines in multiple regional hubs rather than a few centralized facilities, has emerged as a crucial strategy. This approach ensures timely access, reduces reliance on international supply chains, and builds local resilience.

Key benefits of distributed manufacturing include:

- Reduced logistical bottlenecks: local and regional facilities help avoid delays caused by export bans, border closures, or shipping disruptions [23]
- Capacity building: establishing manufacturing in LMICs strengthens local scientific expertise, infrastructure, and self-reliance [24]
- Greater responsiveness: in future health emergencies, this model enables faster development, production, and distribution of vaccines tailored to regional needs [25]

Notable initiatives are already underway. The WHO's mRNA vaccine technology transfer hub in South Africa is a landmark effort aimed at transferring the skills, technology, and intellectual property needed for mRNA vaccine production in LMICs [26]. Similar initiatives can help empower countries to produce vaccines for COVID-19, influenza, HIV, and other emerging diseases.

Global vaccine equity is not just a moral imperative; it is a public health and economic necessity. The COVID-19 pandemic has shown that health security cannot be achieved in isolation. Economic and health system disparities between high-income countries and LMICs have contributed to delays in vaccine access, prolonged the pandemic, and damaged trust in global cooperation. By investing in distributed vaccine manufacturing, the international community can reduce dependency, promote health sovereignty in LMICs, and create a more resilient, equitable global health landscape.

Lessons from COVID-19: centralized production bottlenecks, export bans, and the vulnerability of LMICs

The COVID-19 pandemic exposed major weaknesses in global supply chains, disproportionately affecting low- and middle-income countries (LMICs). Key lessons emerged around the risks of centralized production, the consequences of export bans, and the structural vulnerabilities of LMICs in accessing critical health supplies [2].

Building resilience through decentralization and equity

The pandemic underscores the urgent need to decentralize production and strengthen local manufacturing in LMICs. Investing in regional vaccine and medicine

TABLE 1

Vaccine manufacturing progress: comparative analysis

Region	Leading countries	Key manufacturers/ institutes	Key developments	Key challenges	References
Asia	India, Bangladesh, Indonesia	Serum Institute, Bharat Biotech, Biological E, Incepta, SQUARE Pharma, Bio Farma	India is a major global supplier; Bangladesh and Indonesia are expanding domestic and regional vaccine roles	Technological gaps in mRNA production, cold chain logistics issues, and regulatory delays persist	[26,29–32]
Africa	Senegal, South Africa, Egypt, Rwanda	Institute Pasteur de Dakar, Biovac, Afrigen Biologics, VACSERA, BioNTech (Rwanda)	Rwanda hosts BioNTech's mRNA BioNTainer facility (2023); Senegal is advancing the MADIBA project; Egypt is expanding VACSERA's capabilities	Infrastructure and skilled labor shortages, tech transfer hurdles, and regulatory complexities remain key challenges	[33–36]
Americas	Bolivia, Haiti	AGEMED (Bolivia, planned); none in Haiti	Bolivia is planning domestic capacity; Haiti relies on COVAX and NGOs for supply	The region faces infrastructure deficits, no local production, and complete reliance on imports	[37–39]

production can reduce dependency and increase resilience. Additionally, reforms to global institutions, such as the World Trade Organization are needed to regulate export bans during health emergencies and uphold equitable access to essential goods. While initiatives like COVAX aimed to bridge these gaps, they fell short due to inadequate funding and vaccine nationalism. A stronger commitment to multilateral cooperation and equitable distribution mechanisms is essential for future preparedness [27,28].

LOCALIZED VACCINE MANUFACTURING IN LMICS

A critical step in the supply chain

The drive to localize vaccine manufacturing in LMICs has yielded notable progress, particularly in Asia. However, deep regional disparities persist. Africa and Latin America face more severe constraints, with limited domestic production and high dependence on imports (Table 1). Closing these gaps will require sustained investment in biotechnological infrastructure, workforce training, regulatory harmonization, and equitable access to technology. Public-private partnerships and global collaborations such as those seen in South Africa and Senegal, can serve as models to accelerate vaccine independence. A more equitable and resilient global vaccine ecosystem hinges on empowering LMICs to manufacture vaccines not just for their own populations, but for the world.

Asia: examples of active manufacturing of vaccines

These include the production of active pharmaceutical ingredients (APIs), formulation, fill-finish, quality control, and regulatory oversight. Such countries often have WHO-prequalified facilities and established regulatory systems, enabling them to supply vaccines both domestically and internationally. For example, India, Bangladesh and Indonesia, have played important roles in the global vaccine supply chain. India is home to major manufacturers like the Serum Institute of India, which produce and export large volumes of vaccines. Bangladesh also contributes

through Incepta Vaccine Ltd, which are expanding their production and export capacity. Indonesia, well known for the manufacturing capabilities of PT Biofarma. For instance:

- **Serum Institute of India (SII)**: the world's largest vaccine manufacturer by volume, SII produces key vaccines such as those for polio, diphtheria-tetanus-pertussis (DTP), measles, and COVID-19 (COVISHIELD, developed with AstraZeneca) [40]

- **Bharat Biotech**: developed India's first indigenous COVID-19 vaccine, Covaxin®, and is a leader in rotavirus and rabies vaccines [41]

- **Biological E Ltd**: partnered with CEPI (Coalition for Epidemic Preparedness Innovations) and PATH (Program for Appropriate Technology in Health) to manufacture affordable vaccines, including a protein subunit COVID-19 vaccine (Corbevax) [42]

India's vaccine manufacturing capacity has been essential to global health, especially through the COVAX initiative. Yet, it faces persistent challenges: cold chain logistics, regulatory constraints, and limited capacity for next-generation vaccines like mRNA formulations [5].

In Bangladesh, companies such as Incepta Vaccine Ltd and SQUARE Pharmaceuticals have emerged as significant contributors to regional supply, manufacturing vaccines for influenza, tetanus, and hepatitis B [43,44]. Incepta also plans to expand its fill-finish and bulk manufacturing capabilities [43].

Indonesia's Bio Farma is another key regional player, producing a broad portfolio of vaccines and collaborating with international partners to co-develop and scale vaccine innovation. The company has partnered with organizations like the Coalition for Epidemic Preparedness Innovations (CEPI) and MSD (Merck & Co.) to boost vaccine development and local manufacturing [45,46].

Africa: emerging capabilities amid structural constraints

In Africa, vaccine manufacturing remains at an early stage, with over 90% of vaccines still imported, however several countries across the continent are pursuing targeted initiatives to strengthen local production and reduce reliance on external suppliers [47,48]. For instance:

- **Senegal**: the Institut Pasteur de Dakar has a long-standing history of vaccine production, especially for yellow fever. The Manufacturing in Africa for Disease Immunization and Building Autonomy (MADIBA) project, supported by the European Union and CEPI, is building Africa's first regional manufacturing hub for mRNA vaccines [26]

- **South Africa**: the Biovac Institute, a public–private partnership, has collaborated with Pfizer and Moderna for fill-and-finish capabilities of COVID-19 mRNA vaccines. Additionally, Afrigen Biologics—the lead institution in WHO's mRNA technology transfer program—is working to develop an African-owned mRNA vaccine for COVID-19, with plans to expand to tuberculosis and HIV [26]

- **Egypt**: the state-owned VACSERA has scaled up production of Sinovac and AstraZeneca vaccines under local licenses. Egypt aims to expand its portfolio and become a manufacturing hub for Africa and the Middle East [49]

- **Rwanda**: a landmark development took place in December 2023, when BioNTech inaugurated its first

BioNTainer mRNA vaccine production facility in Kigali. These modular manufacturing units are designed to produce up to fifty million doses annually. The facility will manufacture vaccines targeting malaria, tuberculosis, and HIV and is expected to become operational in 2025. This is part of BioNTech's commitment to decentralizing vaccine production and building capacity in LMICs. The project received a €40 million investment from the European Union through the Global Gateway Africa-Europe Investment Package [50–52]

The Americas: still largely dependent on imports

Vaccine manufacturing in the Americas is uneven. While upper-middle-income countries like Brazil and Mexico have existing capabilities, lower-income countries such as Haiti and Bolivia face significant barriers:

- **Haiti** lacks local production entirely and depends on donor support from COVAX and organizations like GHESKIO and Partners In Health for vaccine access and distribution [53–55]

- **Bolivia** has announced initiatives to develop domestic manufacturing, including through AGEMED (Agencia Estatal de Medicamentos y Tecnologías en Salud), but lacks operational facilities or export capacity as of 2024. The region requires substantial international support to overcome foundational deficits in biomanufacturing and regulatory oversight [56,57]

WHAT NUMBER, SIZE, AND TYPE OF FACILITIES ARE SUSTAINABLE?

Achieving sustainable vaccine manufacturing in LMICs requires strategic planning across three core dimensions: the number of facilities, their size and capacity, and the type of technologies employed. Each of these factors influences a country or region's ability to meet disease control targets, maintain resilience in crisis, and ensure long-term economic viability [5,48].

Number: regional versus national hubs

The optimal number of facilities in LMICs depends on population needs, disease burden, and integration within regional supply chains. Rather than every country building its own end-to-end production capacity, an approach that can be economically inefficient and technologically redundant, a more sustainable model prioritizes regional hubs with satellite fill-finish or distribution nodes.

- WHO's 2030 goal for expanding manufacturing capacity in LMICs suggests a minimum of 15–20 regional vaccine production hubs across Africa, Asia, and Latin America to cover basic immunization needs and prepare for pandemics [48]

- Africa CDC's ambition is to produce 60% of the continent's vaccines by 2040. This would require at least 5–7 strategically located full-cycle manufacturing facilities, supplemented by multiple fill-finish plants to ensure regional distribution [58]

In this model, Rwanda's BioNTech plant [50], Senegal's MADIBA project [35], and South Africa's Biovac/Afrigen [59] hubs serve as early examples of regional manufacturing anchors.

Size: balancing economies of scale versus resilience

Large-scale centralized plants, like India's Serum Institute, offer significant economies of scale, driving down per dose costs and enabling mass export. However, such

TABLE 2

LMIC facilities categorisation.

Type	Description	Pros	Cons	References
Fill-finish only	Importing bulk vaccine materials and packaging locally	Faster setup, lower cost, useful for emergencies	Dependent on bulk imports; limited independence	[65,66]
End-to-end traditional	Local production of antigens, formulation, quality control, packaging	Greater autonomy; can target endemic diseases	Higher cost, longer timelines, complex regulation	[61,67]
mRNA/next-gen platforms	Production of nucleic acid vaccines with modular bioreactors (e.g., BioNTainers)	Rapid scale-up, flexible disease targeting	High-tech demand, IP barriers, new regulatory pathways	[68,69]

facilities are less agile during regional disruptions (e.g., export bans, raw material shortages) [60–62].

By contrast, smaller, decentralized facilities may lack scale efficiency but offer greater resilience, especially during pandemics or geopolitical disruptions. They can [23,63]:

- Serve localized outbreaks faster
- Be customized for regional disease profiles (e.g., Lassa fever, dengue)
- Avoid overdependence on one or two mega-producers

A hybrid approach with large regional hubs supported by modular or mid-sized satellite units, offers the best balance for LMICs. The goal is 'right-sized infrastructure': scalable, affordable, and integrated with public health systems [23,64].

Type: fill-finish versus full end-to-end manufacturing

LMIC facilities can be categorized into three types (Table 2):

In this context, Rwanda's BioNTech BioNTainer facility represents a breakthrough in modular mRNA vaccine production [50,52,68]:

- BioNTainers are fully contained, scalable manufacturing units that can be assembled in under 6 months
- Rwanda's facility is designed to produce up to 50 million doses annually and may serve as a template for rapid deployment in other regions
- The project emphasizes technology transfer, local workforce training, and long-term sustainability

Similarly, Afrigen Biologics in South Africa, as part of WHO's mRNA tech-transfer hub, is another example of how platform-based, modular production can diversify regional vaccine options beyond COVID-19 to include HIV, TB, and malaria [26].

The role of modular, scalable manufacturing technologies

Emerging technologies like modular biomanufacturing, exemplified by BioNTech's BioNTainer, are transforming how LMICs can enter and scale in vaccine production [68,70]:

- Benefits [71–73]:
  - Rapid deployment in underserved regions

- Flexible platform for multiple pathogens
- Lower capital investment than traditional factories
- Enhanced standardization and quality assurance

- Limitations [74,75]:
  - Initial dependence on proprietary technologies and partners
  - Regulatory harmonization is still evolving
  - Requires skilled workforce and digital monitoring capabilities

As of 2024, modular production is becoming the preferred model for sustainable, scalable manufacturing in LMICs, especially in regions with fragile infrastructure but high demand for epidemic and endemic disease response.

A sustainable vaccine manufacturing strategy in LMICs must align with regional public health goals, economic efficiency, and technological viability. Instead of duplicating full production capabilities in every country, a network of regional hubs supported by modular facilities and local fill-finish units represents the most pragmatic model [25]. Rwanda's BioNTainer, Senegal's MADIBA, and India's legacy model illustrate different successful approaches adapted to local needs and global supply demands.

SUPPORTING LMIC VACCINE MANUFACTURING

To accelerate vaccine manufacturing capabilities in low- and middle-income countries (LMICs), targeted short-term policy interventions are essential. These measures can catalyze local production while addressing structural barriers. One such intervention is the use of advance market commitments (AMCs), which reduce investment risk for manufacturers by guaranteeing demand. For instance, Gavi's AMC for pneumococcal vaccines successfully incentivized supply at lower prices for LMICs [76]. Similarly, regional pooled procurement mechanisms, like the Pan American Health Organization (PAHO) Revolving Fund, have proven effective in negotiating better pricing and ensuring equitable distribution [77].

Technology transfer initiatives also play a pivotal role. The World Health Organization's mRNA technology transfer hub in South Africa is a key example, enabling LMICs to build capacity for producing next-generation vaccines. These hubs support knowledge sharing and help overcome intellectual property and technical barriers that often hinder vaccine production in lower-income settings [26].

Streamlining regulatory processes is another critical area. Regulatory harmonization and fast-tracking mechanisms, such as those spearheaded by the African Medicines Agency (AMA), which became operational in 2021, aim to unify standards across the continent. This reduces duplication and facilitates quicker approvals for medical products, thereby expediting vaccine availability [78].

Lastly, financial tools such as initial subsidies, tax incentives, and blended finance can significantly de-risk early-stage investments in vaccine manufacturing. Measures like time-bound subsidies and tax relief for vaccine-related research and development are essential. Blended finance models that combine public and private capital, as demonstrated by the Coalition for Epidemic Preparedness Innovations (CEPI) and the International Finance Corporation (IFC), have shown strong potential to engage the private sector in health manufacturing efforts [79,80].

However, building vaccine manufacturing capacity in LMICs cannot be a one-way

transfer of technology and resources. High-income countries, while providing much-needed support, must also ensure that their assistance does not create dependency. Sustainable vaccine manufacturing in LMICs requires coordinated efforts from national governments, regional bodies, global health organizations (e.g., WHO, Gavi, CEPI), donor agencies, private manufacturers, academic institutions, and civil society. These actors collectively enable local capacity, reduce dependency on external suppliers, and support long-term health security and equity. Bilateral development agencies have a critical role to play in fostering this autonomy. Through investments in infrastructure, training, and local innovation, high-income countries can help build self-sufficient systems without creating a dependence on external aid. For example, the European Union's support for Africa's vaccine manufacturing initiative, which focuses on increasing local manufacturing capacity, emphasizes long-term sustainability and self-reliance [81]. This shift from aid to partnership is essential for ensuring that LMICs can produce vaccines independently and sustainably.

RECOMMENDATIONS AND STRATEGIC ROADMAP

To enhance vaccine manufacturing capabilities in low- and middle-income countries (LMICs), a strategic, phased approach is crucial, involving coordinated action across local, regional, and global stakeholders. Immediate actions must focus on strengthening foundational infrastructure, technology transfer, and regulatory frameworks, while long-term goals should concentrate on scaling production, fostering innovation, and ensuring sustainability [2].

Immediate priorities (0–5 years)

At the local level, governments must invest in building robust regulatory environments, strengthening public health institutions, and incentivizing domestic vaccine manufacturing through financial support and tax relief. Partnerships with multinational pharmaceutical companies for technology transfer and knowledge-sharing are essential for rapid capacity building [26]. Regionally, collaborative frameworks like the African Union's Partnerships for African Vaccine Manufacturing (PAVM) should be expanded, facilitating pooled procurement and shared resources. On the global stage, multilateral organizations such as Gavi and CEPI must continue their support for R&D and infrastructure development, with an emphasis on equitable access and resource sharing [82].

Mid-term actions (5–10 years)

In the next 5–10 years, the focus should shift to scaling up production, developing domestic supply chains, and fostering local innovation. LMICs should work toward achieving greater self-reliance in vaccine manufacturing, reducing dependency on external sources. Regional networks should be strengthened, facilitating better coordination and standardization across countries to ensure equitable distribution during global health emergencies. At the global level, governance structures must be established or refined to ensure the fair distribution of resources and vaccines, addressing issues of intellectual property flexibility, and ensuring that vaccines are produced where they are most needed [83].

FINAL REMARKS

Building long-term vaccine manufacturing capacity in low- and middle-income countries (LMICs) is not just a technical necessity but a critical investment in resilience, sovereignty, and equity. The COVID-19 pandemic revealed the vulnerabilities of a global health system heavily reliant on

external vaccine suppliers, leaving LMICs exposed to supply chain disruptions and limited access to life-saving vaccines. By establishing robust local manufacturing capacities, LMICs can secure their own health futures, reduce dependence on foreign vaccine producers, and be better prepared for future pandemics. Vaccine sovereignty enables nations to prioritize the health needs of their populations, respond rapidly in emergencies, and address the specific disease burdens they face.

However, local vaccine manufacturing is not simply a technical challenge; it is a deeply political and economic project. Achieving this goal requires strong political will, targeted investment in infrastructure, and the development of sustainable regulatory frameworks. It also necessitates the creation of strategic partnerships between governments, international organizations, and the private sector to ensure that knowledge, resources, and technologies are effectively transferred and adapted to local contexts.

Ultimately, sustained collaboration and investment are essential to achieving long-term success. This is a shared global responsibility that demands action from all stakeholders, including national governments, multilateral organizations, and the private sector. It is crucial that efforts are coordinated and sustained over time to create an ecosystem that fosters innovation, promotes equity, and guarantees access to vaccines for all. By taking bold, decisive steps now, we can empower LMICs to lead in vaccine manufacturing, ensuring a more equitable, resilient, and sustainable global health system for generations to come.

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AUTHORSHIP & CONFLICT OF INTEREST

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