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A Systematic Review of Technological Interventions Against COVID-19 in Latin America

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Resumen: Esta investigación revisa sistemáticamente las intervenciones tecnológicas implementadas en América Latina durante la pandemia de COVID-19. El objetivo general del trabajo es evaluar el impacto de estas innovaciones y su efectividad para abordar los desafíos específicos del sistema de salud en la región. Se utilizó una metodología de revisión sistemática integral, identificando estudios relevantes a través de bases de datos como IEEE Xplore, Scopus y PubMed, aplicando el marco PICO para garantizar un examen exhaustivo. La revisión se centra en diversas tecnologías, incluyendo la telemedicina, herramientas de inteligencia artificial (IA), aplicaciones móviles de salud y ventiladores de bajo costo. Estas innovaciones desempeñaron un papel crucial al aliviar la presión sobre los sistemas de salud, permitiendo consultas remotas, mejorando el monitoreo de pacientes y proporcionando soporte respiratorio accesible durante momentos críticos.

Sin embargo, a pesar del éxito inicial de estas intervenciones, la integración a largo plazo de estas tecnologías en los sistemas de salud pospandemia sigue siendo incierta. Persisten barreras como la infraestructura inadecuada, la falta de financiamiento y los obstáculos regulatorios, que continúan dificultando su adopción y escalabilidad generalizada. La revisión destaca la necesidad urgente de políticas de apoyo, mejoras en la infraestructura digital y esfuerzos colaborativos entre los sectores público y privado. Estas medidas son esenciales para garantizar el uso continuo, el desarrollo y la integración de estos avances tecnológicos en los sistemas de salud de América Latina, fortaleciendo así la respuesta de la región ante futuras crisis sanitarias.

Palabras clave: COVID-19, intervenciones tecnológicas, América Latina, telemedicina, herramientas de IA, ventiladores de bajo costo, innovación en salud.

Abstract: This research systematically reviews the technological interventions deployed in Latin America during the COVID-19 pandemic. The general objective of the work is to evaluate the impact of these innovations and their effectiveness in addressing the healthcare challenges specific to the region. A comprehensive systematic review methodology was used, with relevant studies identified through databases like IEEE Xplore, Scopus, and PubMed, employing the PICO framework to guarantee a thorough examination. The review focuses on various technologies, including telemedicine, artificial intelligence (AI) tools, mobile health applications, and low-cost ventilators. These innovations played a crucial role in alleviating the strain on healthcare systems by enabling remote consultations, enhancing patient monitoring, and providing affordable respiratory support during critical times.

However, despite the initial success of these interventions, the long-term integration of such technologies into post-pandemic healthcare systems remains uncertain. Persistent barriers, such as inadequate infrastructure, insufficient funding, and regulatory hurdles, continue to obstruct their widespread adoption and scalability. The review highlights the urgent need for supportive policies, improved digital infrastructure, and collaborative efforts between public and private sectors. These measures are essential to ensure the continued use, development, and integration of these technological advancements into the healthcare systems of Latin America, thereby strengthening the region's response to future health crises.

***Keywords*:** COVID-19, technological interventions, Latin America, telemedicine, AI tools, low-cost ventilators, healthcare innovation.

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Introduction

In December 2019, a novel betacoronavirus named 2019-nCoV, was identified in Wuhan, China, becoming the seventh known coronavirus to infect humans and triggering a global public health response to control its spread (Zhu et al., 2020). By early 2020, the virus was renamed SARS-CoV-2, and the disease it causes was named COVID-19 (Yüce, Filiztekin, & Özkaya, 2021). As of June 2024, COVID-19 has resulted in approximately 7 million deaths worldwide, with a particularly severe impact on Latin America, a region characterized by significant healthcare and socioeconomic disparities (World Health Organization, 2024). Brazil reported the first case of COVID-19 on February 26, 2020, followed by the first death in Argentina on March 7, 2020 (Schwalb, Armyra, Méndez-Aranda, & Ugarte-Gil, 2022). By March 19, 2020, every country in Latin America had confirmed SARS-CoV-2 infections (Johns Hopkins Coronavirus Resource Center, 2024).

The COVID-19 pandemic created a massive strain on public health systems globally, particularly in Latin America. The region's existing challenges, including limited healthcare infrastructure and economic instability, required urgent, innovative solutions to combat the virus. In response, Latin America deployed various technological interventions (Garcia et al., 2020), including telemedicine platforms, artificial intelligence (AI) tools, mobile health applications, and low-cost ventilators. These technologies became essential for healthcare delivery, enabling remote consultations, improving patient monitoring, and offering affordable respiratory support to manage the overwhelming healthcare demand during the pandemic.

This research seeks to systematically review and evaluate the effectiveness of these technological interventions across the region, addressing the research problem of understanding their impact and the challenges encountered during their implementation. The main objective of this study is to identify how these technologies contributed to healthcare delivery and assess their potential for long-term integration into post-pandemic health systems.

The hypothesis posits that while these technologies were critical in responding to the crisis, their adoption and scalability were limited by systemic barriers, such as inadequate infrastructure, funding constraints, and regulatory hurdles. The methods employed in this research include a systematic review of existing studies on technological innovations implemented in Latin America during the COVID-19 pandemic. A detailed analysis was conducted using databases like IEEE Xplore, Scopus, and PubMed, structured through the PICO framework to ensure comprehensive coverage of the interventions, comparisons with pre-pandemic processes, and success rates.

The most relevant conclusions from this review highlight the need for stronger public-private collaborations, enhanced digital infrastructure, and supportive policy reforms. These elements are essential to ensure the continued use and development of these innovations in Latin America's healthcare systems, addressing the systemic barriers that hinder their broader adoption. The findings from this study are particularly significant for shaping future public health policies and guiding technological advancements in other regions with similar socioeconomic and healthcare challenges.

This research is organized into four chapters to systematically explore the technological interventions deployed in Latin America during the COVID-19 pandemic. The first chapter provides a comprehensive literature review, focusing on the pandemic's impact on the region and the key technological innovations implemented, such as telemedicine and low-cost medical devices. Chapter II discusses the methodology used, detailing the systematic review process, including search strategies, inclusion criteria, and data extraction. Chapter III presents the results, highlighting the success rates, contributions, and Technology Readiness Levels (TRL) of the interventions. Lastly, Chapter IV offers a discussion of the findings, evaluating the adoption of these technologies, their impact on healthcare systems, and the challenges that limit their long-term sustainability.

Chapter I: State of the Art

1.1. Introduction to COVID-19 and its impact on Latin America

The COVID-19 pandemic, which emerged in Wuhan, China, in December 2019, swiftly escalated into a global health crisis, drastically impacting countries worldwide. By March 2022, the virus had claimed over six million lives globally, with Latin America and the Caribbean (LAC) suffering disproportionately. The region accounted for 15% of global cases and 28% of global deaths, despite representing only 8% of the world's population, making it one of the most severely affected regions globally (Schwalb, Armyra, Méndez-Aranda, & Ugarte-Gil, 2022). The rapid spread of the virus, coupled with pre-existing structural vulnerabilities, exposed the fragility of LAC's healthcare systems and exacerbated longstanding socioeconomic disparities. By May 2022, over 1.7 million COVID-related deaths were recorded in the region, accounting for 27% of global fatalities (Camacho-Leon et al., 2022).

Latin America's healthcare systems faced immense strain as the pandemic unfolded. The region's public healthcare institutions were particularly vulnerable due to chronic underfunding, a lack of infrastructure, and a fragmented system of care divided between public and private sectors. Countries such as Brazil, Mexico, Peru, and Argentina struggled to manage surging COVID-19 cases, as their hospitals quickly became overwhelmed, leading to shortages of medical supplies, intensive care unit (ICU) beds, and healthcare professionals (Camacho-Leon et al., 2022). For instance, Brazil, one of the countries with the highest infection and death rates, saw its hospitals saturated within weeks of the virus's arrival. Similarly, in Peru and Mexico, healthcare systems that were already under-resourced faced immense difficulties coping with the influx of patients, highlighting the region's insufficient preparedness for such a large-scale health emergency.

The socioeconomic landscape of the region further amplified the effects of the pandemic. Widespread poverty, income inequality, and inadequate access to basic healthcare services left many vulnerable populations exposed to the virus with limited means to protect themselves. Rural and indigenous communities, as well as densely populated urban areas with poor living conditions, experienced higher transmission rates and mortality due to a lack of healthcare access and poor infrastructure (Augustovski et al., 2023). The pandemic exposed the stark reality of unequal healthcare distribution in Latin America, where those with the least access to care were often the most severely affected.

In response to these challenges, governments across Latin America adopted various public health measures, including lockdowns, social distancing mandates, and widespread testing. Countries like Argentina, Brazil, and Mexico led efforts to mitigate the pandemic's spread by implementing strict public health interventions. However, the region's response was hampered by logistical challenges, insufficient healthcare resources, and delayed vaccine rollouts. The early reliance on repurposed treatments like hydroxychloroquine and ivermectin, fueled by misinformation, further complicated pandemic management efforts, leading to poor adherence to scientifically validated public health guidelines (Schwalb, Armyra, Méndez-Aranda, & Ugarte-Gil, 2022).

As traditional healthcare delivery was disrupted due to lockdowns and the risk of viral transmission, Latin American countries turned to technological innovations to manage the crisis. Telemedicine, a previously underutilized tool in the region, gained significant importance during the pandemic. It enabled healthcare providers to continue treating patients remotely, reducing the burden on overcrowded hospitals and minimizing the risk of infection from in-person visits. Countries such as Ecuador, Chile, and Uruguay were early adopters of telemedicine, rapidly deploying digital health platforms to maintain patient care, especially in rural and underserved regions (Pinto et al., 2022).

Despite its benefits, the implementation of telemedicine in Latin America faced considerable challenges. The region's digital infrastructure, particularly in rural areas, was inadequate to support large-scale telemedicine initiatives. Limited broadband coverage, lack of access to digital devices, and disparities in digital literacy among patients created barriers to widespread adoption. Moreover, regulatory frameworks governing telemedicine were often inconsistent or outdated, impeding efforts to integrate telehealth services fully into healthcare systems (Camacho-Leon et al., 2022). Nonetheless, telemedicine proved to be a critical lifeline during the pandemic, allowing for continued care in a time of crisis.

The COVID-19 pandemic not only tested the resilience of Latin America's healthcare systems but also underscored the importance of international collaboration in addressing public health emergencies. Regional organizations, such as the Pan American Health Organization (PAHO), played a key role in coordinating pandemic response efforts. PAHO provided technical assistance, supported the expansion of hospital capacity, and facilitated the procurement of critical medical supplies, including vaccines and personal protective equipment (Nardi, Ginsbach, Aneja, Gottschalk, & Halabi, 2023). The COVAX initiative, a global effort to ensure equitable access to vaccines, was instrumental in distributing vaccines across the region, though vaccine rollouts were delayed due to supply chain issues and geopolitical complexities.

Despite the challenges, the pandemic catalyzed the adoption of new technologies and innovations in healthcare across Latin America. Countries like Argentina, Brazil, and Colombia advanced the use of telemedicine, artificial intelligence (AI), and digital health platforms to manage the pandemic's impact (Hoff, Ponce, & Sossa, 2021). AI applications were particularly useful in enhancing diagnostic capabilities, monitoring social distancing, and predicting the progression of COVID-19 outbreaks. These technological advancements highlighted the region's potential for innovation in times of crisis, though they also emphasized the need for stronger healthcare systems, better access to digital technologies, and more equitable resource distribution.

1.2. Telemedicine and Remote Care in Latin America

The COVID-19 pandemic transformed healthcare across Latin America, accelerating the adoption of telemedicine and remote care. As hospitals and healthcare systems faced overwhelming pressure, telemedicine emerged as a crucial tool to deliver healthcare services while minimizing in-person contact, thereby reducing the spread of the virus. This shift was not only a response to the pandemic but also highlighted the long-term potential of telemedicine in addressing the region's pre-existing challenges in healthcare accessibility, particularly in rural and underserved areas of Brazil, Colombia, Peru and Argentina.

1.2.1. Digital Transformation and the Role of Telemedicine

During the pandemic, healthcare institutions in Brazil, Chile and Colombia rapidly adapted their digital infrastructures to facilitate telemedicine. As noted in Tejedor, Pérez-Escoda, Ventín, Tusa, and Martínez (2020), hospital websites became essential platforms for delivering telemedicine services and managing virtual consultations. This integration allowed patients in both urban and rural areas to access healthcare remotely, maintaining continuity of care even during lockdowns. Brazil's Albert Einstein Hospital being notable examples of institutions excelling in both telemedicine and digital communication.

1.2.2. Telemedicine for Emergency Care

In Colombia, the "Siempre" teleconsultation program, implemented at Fundación Valle del Lili (FVL), exemplified how telemedicine could alleviate pressure on emergency services. The program facilitated virtual care for patients experiencing urgent health issues, reducing the number of in-person visits and helping healthcare providers manage the overwhelming number of COVID-19 cases. This program proved highly effective, registering over 4,600 consultations, demonstrating telemedicine's capacity to address immediate healthcare needs without exposing patients and staff to unnecessary risks (Libreros-Peña, Quintero, & Gelves, 2023).

1.2.3. Integration with Public Health Measures

Telemedicine also complemented other public health interventions, such as contact tracing, which played a significant role in reducing COVID-19 fatalities in Colombia. As highlighted in Fernández-Niño, Peña-Maldonado, Rojas-Botero, and Rodriguez-Villamizar (2021), combining telemedicine with contact tracing allowed for better monitoring and management of at-risk individuals. By ensuring that infected patients were identified and managed remotely, healthcare systems could reduce hospitalizations and focus on critical cases.

1.2.4. Barriers to Telemedicine Adoption

Despite these successes, countries like Peru, Colombia and Mexico faced significant barriers in implementing telemedicine. As discussed in Martinez-Valle (2021), socioeconomic disparities, digital infrastructure deficiencies, and healthcare inequalities limited the widespread adoption of telemedicine in some countries. Peru, for instance, faced severe limitations in its public health infrastructure, which prevented telemedicine from reaching its full potential, particularly in rural and impoverished areas.

1.2.5. International Support and Regulatory Challenges

In countries like Brazil, Peru and Mexico, the rapid adoption of telemedicine was supported by global organizations like the World Health Organization (WHO) and the Pan American Health Organization (PAHO), as highlighted in Saigí-Rubió (2023). WHO Collaborating Centers in eHealth, such as the Universitat Oberta de Catalunya, played a pivotal role in providing technical assistance to implement telemedicine services. However, legislative differences across countries and the digital divide remained significant barriers to its broader integration.

1.2.6. Enhancing Diagnostics Through Telemedicine

Countries like Chile and Argentina advanced the use of telemedicine by integrating point-of-care (POC) rapid testing. In Alvarez-Moreno et al. (2024), the use of rapid diagnostic tools allowed for quick decision-making during virtual consultations. This synergy between point-of-care testing and telemedicine minimized the need for hospital visits, improving patient outcomes by enabling timely, remote diagnoses.

1.2.7. Technological Innovations and Robotics in Remote Care

In Brazil, Argentina, Colombia and Peru, technological innovations complemented telemedicine efforts as described in Bejarano, Navarro, and Marín García (2021)**.** Innovations such as electronic health records (EHRs), 3D printing, and remote health management platforms enhanced the management of healthcare systems and reduced the administrative burden on hospitals.

1.2.8. Telemedicine and Robotic Integration

In Brazil and Colombia, robots were deployed to complement telemedicine services by supporting remote monitoring and reducing the risk of virus exposure for healthcare professionals. The study of Sierra Marín et al. (2021), notes how telemedicine robots were used for remote consultations, enabling healthcare workers to monitor patients while minimizing physical contact.

1.2.9. Sanitization and Remote Healthcare Platforms

Countries like Chile and Brazil also saw the integration of autonomous robotic systems, such as the COVID-Bot, discussed in Camacho, Ospina, and Calderón (2021). These robots played a significant role in maintaining sanitized environments, ensuring that hospitals were safer for healthcare workers to perform remote care operations.

1.2.10. Cloud-Based Mobile Manipulation

Lastly, in Argentina and Brazil, Varela-Aldás, Buele, Guerrero-Núñez, and Andaluz (2022) underscores how cloud-based robotics integrated with telemedicine platforms, allowing healthcare workers to remotely monitor and control mobile manipulators. This further advanced the ability to provide efficient care without the need for direct physical interaction with patients.

1.3. Artificial Intelligence and Machine Learning Tools

The COVID-19 pandemic caused the integration of Artificial Intelligence (AI) and Machine Learning (ML) in healthcare, transforming diagnostic processes and enhancing clinical decision-making. In Latin America, the implementation of these technologies has played a crucial role in managing the pandemic by optimizing patient care, predicting disease outcomes, and improving resource allocation. This section provides an overview of how AI and ML tools were applied across various countries in the region to address the challenges posed by the COVID-19 crisis.

1.3.1. AI for Early Diagnosis in Low-Resource Settings

AI proved indispensable in low- and middle-income countries (LMICs) like Brazil, Mexico, Argentina, and Colombia, where healthcare systems faced severe limitations during the pandemic. Goncalves, Fong, and Blokhina (2022) highlights the use of AI to process vast amounts of medical imaging, such as chest X-rays (CXR) and computed tomography (CT) scans. These technologies, originally intended for lung cancer diagnosis, were adapted to screen for COVID-19-related complications, showcasing AI's versatility in diagnostics in resource-constrained environments.

Latin American countries utilized AI tools to identify incidental pulmonary nodules (IPNs) in routine imaging, which not only helped with early lung cancer detection but also improved screening for other diseases. Given the shortage of radiologists in the region, AI-assisted radiography became a pivotal tool for early detection in primary healthcare settings, particularly in rural areas.

1.3.2. Predictive Tools for Clinical Outcomes

AI and ML models were also employed to predict the clinical outcomes of COVID-19 patients, aiding healthcare systems under strain. The study Klén et al. (2022) presents a predictive tool developed using data from over 29,223 patients across hospitals in Argentina, Honduras, and Bolivia. The CODOP tool, trained on 12 clinical parameters, achieved high accuracy (AUROC 0.90-0.96) in predicting mortality risk up to nine days before clinical resolution.

CODOP demonstrated stability across multiple waves of the pandemic, including those involving the Delta and Omicron variants. It was tested in various hospital settings, offering valuable triage tools for resource-limited healthcare systems in Latin America. The model's simplicity and effectiveness, combined with online calculators, allowed for rapid adoption across the region.

1.3.3. AI-Driven Diagnostics with Chest X-Rays

In Peru, where healthcare systems faced tremendous pressure during the pandemic, AI became an essential tool for diagnosing COVID-19. Alvarado-Díaz and Meneses-Claudio (2021) presents an AI-based model that utilized Convolutional Neural Networks (CNNs) to identify COVID-19 and other respiratory diseases, such as bacterial and viral pneumonia, from chest X-ray images. The model achieved an accuracy of approximately 80%, offering a cost-effective solution in regions where access to PCR tests was limited.

The study also developed a graphical interface to allow healthcare workers to upload X-ray images, receive AI-based predictions, and store results for future consultations. This interface was particularly valuable for healthcare providers in remote and underserved areas, helping them make quick and informed diagnoses. The success of this AI tool in Peru demonstrated the importance of scalable, technology-driven solutions to meet the diagnostic needs of low-resource settings.

1.3.4. Machine Learning for Clinical Screening and Severity Prediction

In Brazil, Paiva de Oliveira, Bastos Filho, de Medeiros, dos Santos, and Lopes Freire (2021) focused on the application of ML models to diagnose COVID-19 using routine clinical laboratory data. The study developed several models, including Random Forest (RF) and Support Vector Machines (SVM), to classify COVID-19 infections with an accuracy of over 96%. This approach provided a rapid, cost-effective alternative to PCR testing, which was often slow and expensive in many parts of Brazil.

The ML models were also applied to predict the severity of COVID-19 cases, allowing healthcare providers to categorize patients based on the required level of care. This model achieved an accuracy of over 92% in classifying patients into intensive care, semi-intensive care, or standard hospitalization categories, optimizing the use of healthcare resources during peak periods of the pandemic.

1.3.5. Transfer Learning with AI for COVID-19 Detection

Cortés and Sánchez (2021) highlights another significant AI application in Brazil. Researchers fine-tuned the AlexNet model, a convolutional neural network (CNN), using over 11,000 chest X-ray images to detect COVID-19 cases. The model achieved an accuracy of 96.5%, making it a reliable tool for rapid COVID-19 diagnosis. This method was particularly effective in low-resource environments where access to CT scans was limited.

The use of transfer learning allowed the researchers to leverage existing models, reducing the time and resources required to develop an effective diagnostic tool. This approach proved especially valuable in rural and underserved areas of Brazil, where healthcare professionals relied on AI-driven diagnostics to identify COVID-19 patients quickly.

1.3.6. Clustering Models for Resource Management

In Colombia, AI and ML tools also assisted in resource management during the pandemic. Orjuela-Cañon and Perdomo (2021) explores the use of clustering algorithms to manage COVID-19 cases in Bogotá. The model applied Self-Organizing Maps (SOM) and Fuzzy ART (Adaptive Resonance Theory) to categorize patients into high, medium, and low-risk groups, based on clinical data.

This AI-driven approach helped healthcare professionals prioritize resources, such as ICU beds and ventilators, and improve patient management. The model's ability to function effectively in data-scarce environments highlights the potential of AI in supporting healthcare decision-making in regions with limited access to comprehensive clinical data.

1.4. Low-Cost Ventilators and Medical Devices

The COVID-19 pandemic led to an unprecedented demand for ventilators and medical devices across Latin America. Many countries in the region, facing severe shortages. In response to these challenges, various Latin American countries developed and deployed low-cost ventilators and other essential medical devices. This chapter reviews key technological interventions and innovations in low-cost ventilators and medical devices during the COVID-19 pandemic, focusing on their impact across several Latin American countries.

1.4.1. The Unisabana-HERONS Ventilator

In Colombia, the Universidad de La Sabana and the Fundación Neumológica Colombiana developed the Unisabana-HERONS ventilator (Giraldo-Cadavid et al., 2024) to address the severe shortage of mechanical ventilators during the pandemic. At a time when global demand for ventilators far exceeded supply, particularly in LMICs, the development of low-cost alternatives became crucial. The cost of conventional ventilators, approximately $30,000, was prohibitively high for many Colombian healthcare facilities, necessitating innovative, cost-effective solutions.

The Unisabana-HERONS ventilator, costing around $3,000, was designed to meet international standards (ISO), offering volume-controlled ventilation and continuous positive airway pressure (CPAP). Clinical trials, including tests on five patients with acute respiratory failure, demonstrated the device's effectiveness. In over 98% of the cases, the ventilator maintained respiratory parameters within safe limits, with no adverse events reported. The ventilator's ease of use was particularly notable, with usability ratings between 9 and 10, ensuring that even non-specialist medical personnel could operate it during emergency situations.

1.4.2. Splitting Ventilator Valve

In Brazil, the COVID-19 pandemic created a situation in which ventilator shortages became critical, especially during the first wave of infections in 2020. To address this, a team of researchers developed a splitting ventilator valve using additive manufacturing (3D printing). The ventilator valve allowed for the simultaneous use of one ventilator on multiple patients, a significant breakthrough in resource-constrained settings (DA Silva et al., 2021).

The valve system was equipped with pressure sensors and flow transducers to ensure the even distribution of air among patients. Automated control systems were integrated to monitor patients' respiratory parameters, reducing the workload on healthcare workers. This innovation allowed hospitals in Brazil to maximize the use of available ventilators, addressing shortages and helping prevent overcrowded intensive care units (ICUs).

1.4.3. Real-Time Stress Index

To improve the safety of low-cost ventilators used in emergency settings, researchers in Colombia developed a real-time stress index that continuously monitored ventilator performance. This index, shown in Caballero et al. (2022), allowed for real-time monitoring of lung compliance and mechanical load on patients' respiratory systems during ventilation. The algorithm used for this index was designed to function in low-resource settings, requiring only basic sensors.

By continuously adjusting ventilation parameters based on real-time data, this index significantly reduced the risk of ventilator-induced lung injury (VILI) and improved patient outcomes. This tool played an important role in enhancing the safety and effectiveness of low-cost ventilators during the pandemic.

1.4.4. Low-Cost CPAP Devices

In Ecuador, the need for non-invasive ventilation devices like Continuous Positive Airway Pressure (CPAP) machines became apparent as hospitals struggled to manage the rising number of COVID-19 patients with respiratory distress (F. S. L., Urrutia, Freire, Jordán, Nuñez, & Pérez, 2022). To address this, Ecuadorian engineers adapted a low-cost CPAP device from the UCL-Ventura model used in the UK. By manufacturing the device locally, Ecuadorian hospitals could avoid the high costs of imported ventilators, estimated to be as much as 70% higher.

The CPAP device provided non-invasive respiratory support for patients with moderate to severe COVID-19 symptoms, preventing the need for invasive mechanical ventilation in many cases. Clinical trials demonstrated that the device could maintain adequate oxygenation levels while consuming up to 70% less oxygen than conventional ventilators, making it particularly valuable in resource-limited settings where oxygen supply was constrained.

1.4.5. Masi Ventilator

The Masi ventilator, developed in Peru by several institutions, including the Pontificia Universidad Católica del Perú (PUCP), was designed to provide both invasive and non-invasive respiratory support during the COVID-19 pandemic. Over 310 units were produced and validated according to international standards, such as those set by the UK's Medicines and Healthcare Products Regulatory Agency (MHRA). These ventilators played a crucial role in Peru's healthcare system, where resources were limited, and hospitals were overwhelmed by the surge of COVID-19 cases.

Quality and Testing: A sample of 30 ventilators underwent rigorous testing to ensure compliance with safety and performance standards, focusing on key parameters like peak inspiratory pressure (PIP) and tidal volume (VT). These tests confirmed that the ventilators met the required tolerance levels (within ±15%), ensuring their safe use in both invasive and non-invasive ventilation modes (Gomez-Alzate, Perez-Buitrago, Cordova, Bornas, & Castaneda, 2021).

Non-Invasive Capabilities: Further developments of the Masi ventilator focused on its non-invasive ventilation (NIV) capabilities, utilizing accessories such as high-flow nasal cannulas (HFCs) and facial masks (FM). Testing revealed that the facial mask provided the most effective and stable respiratory support, significantly reducing the need for invasive ventilation and helping to manage the high demand for ICU beds during the pandemic (Leiva et al., 2022).

High-Altitude Performance: The Masi ventilator was also tested in high-altitude regions like Puno, located 3,800 meters above sea level (Perez-Buitrago et al., 2021). High altitude posed unique challenges for ventilator performance due to reduced atmospheric pressure, particularly affecting tidal volume and pressure control. Initial tests indicated a 25% error in tidal volume, which was corrected through a software update. After recalibration, the ventilators performed within acceptable error margins, making them suitable for use in high-altitude areas across Peru's Andean mountains, thus expanding their applicability.

1.4.6. PytuTester: Ventilator Testing

In Paraguay, the PytuTester was developed to help bioengineers test ventilators produced during the pandemic (Morales et al., 2022). Commercial ventilator testers, costing between $5,000 and $12,000, were prohibitively expensive for many hospitals in Paraguay. The PytuTester, costing only $500, offered an affordable alternative that allowed for the testing and validation of ventilators designed for emergency use.

The PytuTester measured key parameters such as airflow, pressure, and oxygen concentration, providing reliable data to ensure the safety and functionality of ventilators. This device was tested on multiple ventilators developed in Paraguay and proved to be an essential tool for ensuring the safety and efficacy of locally produced ventilators.

1.4.7. Low-Cost Smartband to Prevent COVID-19

In Brazil, Lima Vieira, De Almeida Carlos, and Jose Irineu (2021) developed a low-cost smartband to prevent COVID-19 transmission by reducing hand-to-face contact, a common method of viral transmission. The smartband, which vibrated when the user’s hand approached their face, was designed for mass production using affordable components. A total of 500 units were tested in Alagoas, Brazil, with a success rate of 82% in detecting hand-to-face movements.

This simple yet effective device provided an additional layer of protection for users, complementing traditional preventive measures such as mask-wearing and hand hygiene.

1.4.8. IoMT-Based Rinku Clinical Kit

In Mexico, the Rinku Clinical Kit utilized Internet of Medical Things (IoMT) technology to monitor COVID-19 patients remotely

(Rodriguez et al., 2021). The kit included sensors to track vital signs such as body temperature and oxygen saturation, transmitting this data to healthcare professionals via a cloud-based platform. This technology allowed for remote patient management, reducing hospital overcrowding and lowering the risk of viral transmission.

The Rinku kit was particularly valuable in rural and underserved regions of Mexico, where access to healthcare facilities was limited. By enabling remote monitoring, the kit helped healthcare providers manage the pandemic more effectively.

1.4.9. Low-Cost Volume Sensors for Mechanical Ventilators

In Brazil, Araujo Damasceno et al. (2021) developed low-cost volume sensors to improve the functionality of mechanical ventilators. These sensors, including infrared-based devices, provided accurate measurements of tidal volume, ensuring safe and effective mechanical ventilation for COVID-19 patients. The sensors cost approximately $2.32, a fraction of the price of commercial alternatives, which range from $250 to $800.

This low-cost solution was crucial in a country like Brazil, where ventilator shortages were severe during the pandemic. The volume sensors enhanced the safety and reliability of locally produced ventilators.

1.4.10. Ventilator Development in Chile: "Un Respiro para Chile"

In Chile, the "Un Respiro para Chile" initiative led to the development of the Neyün mechanical ventilator (Bugedo et al., 2022). Faced with a ventilator shortage during the first wave of the pandemic, public and private institutions collaborated to design and produce ventilators locally. The Neyün ventilator, capable of both invasive and non-invasive ventilation, was subjected to rigorous testing in Chilean hospitals before being deployed.

The ventilator's successful development and deployment underscored Chile’s ability to innovate in response to a national health emergency. The project helped alleviate the strain on Chile’s healthcare system and demonstrated the country’s capacity for biomedical innovation.

1.5. Barriers to Technological Implementation in Latin America

The COVID-19 pandemic posed numerous challenges for Latin American countries in terms of health systems, technology adoption, and regulatory pathways. Several factors have slowed the region’s response and ability to implement technological solutions, from regulatory hurdles to socioeconomic disparities. This chapter discusses the barriers faced in the region, based on the analysis of various studies.

1.5.1. Regulatory Challenges and Reliance Pathways

In Latin America, regulatory reliance pathways became critical for the timely authorization of COVID-19 vaccines, as many national regulatory authorities (NRAs) in the region lacked the necessary resources and expertise to deal with health emergencies. A study conducted by van der Zee et al. (2022) highlights that 44.6% of COVID-19 vaccine authorizations in 18 Latin American countries used regulatory reliance pathways. These pathways allowed NRAs to rely on the regulatory work of other agencies, expediting the approval process. However, reliance mechanisms were not uniformly adopted, with reference agencies using them less often (40% of authorizations) compared to non-reference agencies (100%). The median review time for vaccine authorization was 15 days, demonstrating that regulatory reliance facilitated rapid approvals during the pandemic.

The limited capacity of some NRAs and the lack of transparency regarding the regulatory processes in non-reference countries were major barriers. In many cases, agencies had to shift resources, potentially delaying other crucial regulatory work. This reliance on external agencies underscores a broader issue: the underdevelopment of local regulatory systems in many parts of Latin America (Van der Zee, Vreman, Liberti, & Garza, 2022).

1.5.2. Socioeconomic Inequalities and Health System Preparedness

Latin America is a region marked by stark socioeconomic inequalities, which significantly impacted its ability to adopt and implement technological interventions during the pandemic. Martinez-Valle (2021) emphasizes the differences in health system preparedness across the region, with countries like Chile and Argentina being relatively well-prepared in comparison to others like Peru and Brazil. Factors such as public health expenditures, out-of-pocket costs, and maternal mortality rates were used to measure preparedness. For instance, Peru had the lowest public health expenditures and the highest maternal mortality rate, contributing to its struggles in implementing effective technological solutions.

Moreover, socioeconomic disparities, such as income inequality and vulnerable job sectors, made it more difficult for certain countries to enforce pandemic mitigation policies, further hindering technological adoption. In Peru, 45.1% of the population lived in poverty, with 16.3% in extreme poverty, making it one of the most vulnerable nations in the region. This economic vulnerability limited access to healthcare and created barriers to the widespread use of new technologies, including digital health interventions. Moreover, socioeconomic disparities, such as income inequality and vulnerable job sectors, made it more difficult for certain countries to enforce pandemic mitigation policies, further hindering technological adoption. In Peru, 45.1% of the population lived in poverty, with 16.3% in extreme poverty, making it one of the most vulnerable nations in the region. This economic vulnerability limited access to healthcare and created barriers to the widespread use of new technologies, including digital health interventions (Martinez-Valle, 2021).

1.5.3. Public Policy and Trust in Government

The success of public policy implementation during the pandemic was closely tied to public trust in government and compliance with health regulations. In countries like Argentina and Chile, more stringent and timely policy responses contributed to higher mobility reductions and lower mortality rates. On the other hand, Brazil and Mexico, where government leaders downplayed the severity of the pandemic, experienced lower compliance and higher mortality rates. For instance, Argentina's prompt response helped maintain a stringency level of over 80%, which was associated with reduced COVID-19 transmission and improved public health outcomes. The lack of effective communication from governments in Brazil and Mexico created additional barriers to technology adoption. Public distrust and inconsistent messaging hampered the implementation of contact tracing apps, digital health solutions, and telemedicine platforms in these countries (Martinez-Valle, 2021).

Chapter II: Methodology

This chapter describes the systematic approach used in the research to evaluate and analyze technological interventions against COVID-19 in Latin America. The methodology follows a structured process to ensure comprehensive and unbiased review and includes three primary stages: planning, implementation, and reporting. This approach is rooted in systematic review principles, which are critical for synthesizing evidence across multiple studies and ensuring a robust understanding of technological effectiveness and adoption in the region.

2.1. Research Design

The research design is based on a systematic review framework that aims to identify, evaluate, and synthesize relevant literature on COVID-19 technological interventions in Latin America. This design enables the study to answer research questions related to the types of technologies used, their success rates, and the contextual factors affecting their implementation.

The methodology follows the guidelines for systematic reviews as outlined by Tranfield, Denyer, and Smart (2003), emphasizing evidence-based management knowledge. The research uses the PICO (Population, Intervention, Comparison, and Outcome) structure to formulate research questions and define inclusion criteria for selecting studies.

2.2. Search Strategy

The search strategy involved a comprehensive literature search across several electronic databases, including IEEE Xplore, Scopus and PubMed. The search focused on publications from December 2019 to May 2024 to capture studies during the COVID-19 pandemic. The keywords used in the search were tailored to capture a wide range of technological interventions and their applications in Latin America. Key terms include the combinations shown in Table 1.

Table 1: *Seach Terms*

PICO Structure			
Population	***Intervention***	***Comparison***	***Outcome***
Researchers	Development and implementation of new technology	Regulation process	Success rate
Entrepreneurs	Innovative technology	Implementation of existing technology	Impact of technology development
Merchants	New technological solutions	Latin America	Knowledge / Research
Stakeholders in technological development	COVID-19 mitigation	Technology adoption	Market

Technology innovation teams	COVID-19 OR pandemic OR coronavirus OR SARS-CoV-2 response	Regular framework	Technology readiness level (TRL)

These search terms were designed to capture various aspects of technological interventions, focusing on their implementation, outcomes, and barriers. The search was conducted in English, Spanish, and Portuguese to encompass the regional context of Latin America.

2.3. Inclusion and Exclusion Criteria

Studies were included in the review if they met the following criteria:

- **Inclusion Criteria**:
  - Studies that reported the development and implementation of technological solutions to combat COVID-19 in Latin America.
  - Peer-reviewed articles, conference papers, and government reports published in English, Spanish, or Portuguese.
  - Studies that provided quantitative or qualitative data on the effectiveness, success rate, or impact of the technology.
- **Exclusion Criteria**:
  - Theoretical articles without practical implementation data.
  - News articles lacking detailed substantiation of technological outcomes.
  - Studies focused on regions outside Latin America.
  - Articles that discussed political or non-technological responses to the pandemic.

2.4. Data Extraction and Analysis

Data extraction was performed using a standardized template to capture key information from each selected study. The following elements were extracted:

i. **Study Characteristics**: Authors, year of publication, and country.
ii. **Technological Interventions**: Types of technologies used, including telemedicine, AI tools, and ventilator innovations.
iii. **Contextual Factors**: Socioeconomic and healthcare contexts influencing technology adoption.
iv. **Outcomes**: Success rates, challenges, and barriers to implementation.

v. **Technology Readiness Level (TRL)**: The TRL methodology is used to classify the maturity of technologies based on their development and operational readiness. Each technological intervention is assigned a specific TRL based on the extent to which it has been tested, validated, and implemented in real-world conditions. The Technology Readiness Level (TRL) scale consists of nine levels:

- **TRL 1**: Basic principles are observed.
- **TRL 2**: Technology concept or application is formulated.
- **TRL 3**: Experimental proof of concept.
- **TRL 4**: Technology is validated in a lab.
- **TRL 5**: Technology is validated in a relevant environment.
- **TRL 6**: Technology is demonstrated in a relevant environment.
- **TRL 7**: Prototype is demonstrated in an operational environment.
- **TRL 8**: The system is complete and qualified.
- **TRL 9**: The actual system is proven in an operational environment.

This classification helps assess the potential for scalability and long-term adoption of these technologies beyond the pandemic, indicating which interventions are ready for full-scale implementation and which require further development.

The extracted data were analyzed to identify patterns in technology use, success rates, and common barriers across different countries in the region. The results were then categorized by technology type and contextual factors to provide a comprehensive understanding of technological interventions during the pandemic.

2.5. Limitations of the Methodology

While the systematic review provides a broad overview of technological interventions in Latin America, it is limited by the availability of data in some countries. The digital divide in the region, especially in rural areas, may have resulted in underreporting of certain technologies. Additionally, the rapid pace of technological development during the pandemic means that some innovations may not yet be fully documented in the academic literature.

The study’s reliance on published research may also introduce a bias, as technologies developed and implemented by non-academic entities (e.g., local governments, private companies) may not be captured in this review. As a result, the findings should be interpreted with caution, and further research is needed to validate the long-term impact and sustainability of these interventions.

Chapter III: Results

This chapter presents the findings of a systematic review of the technological interventions against COVID-19 implemented across Latin America. The results focus on evaluating the types of technologies used, their effectiveness, and their contributions to healthcare systems in the region. Through detailed analysis of 43 selected articles as shown in Fig. 1, the results are divided into several categories, reflecting the diversity and range of technological applications.

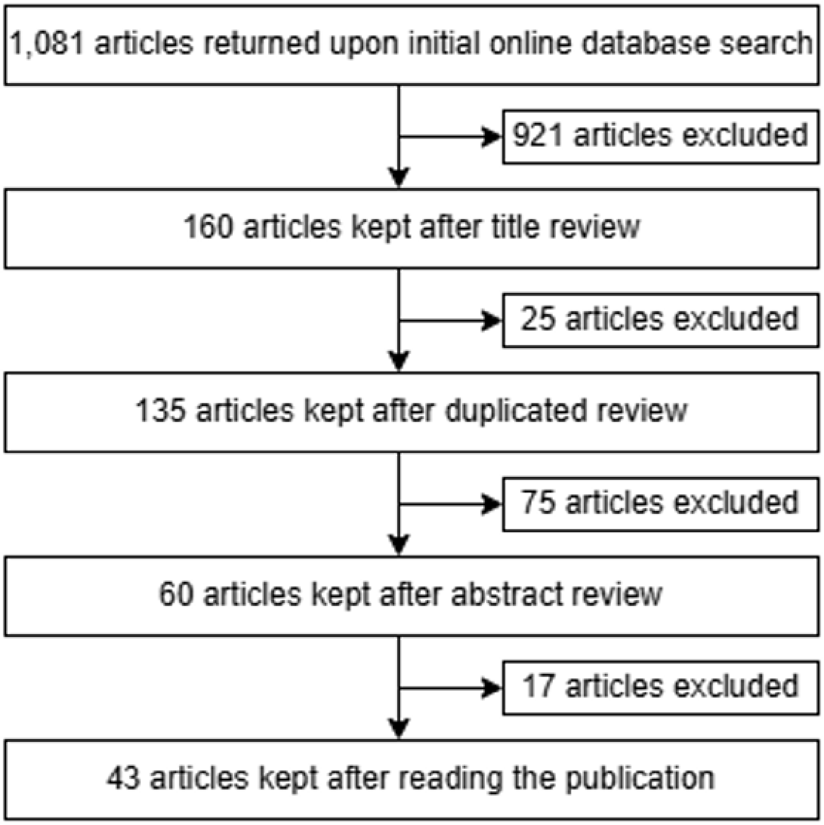

Figure 1: *Search procedure for including articles in review.*

3.1. Overview of the Selected Technological Interventions

The systematic review identified 43 studies that met the inclusion criteria. These studies covered various types of technological innovations used to mitigate the impact of COVID-19 in Latin America, with a primary focus on telemedicine, low-cost ventilators, artificial intelligence (AI) tools, and mobile health applications.

Table 2 shows the types of technologies addressed in the reviewed articles. The total number is not equal to 43 because some studies addressed more than one type of technology.

Table 2: *Technologies Analyzed*

Type of technology	**Number of studies**
Teleconsultation / Telemedicine / Telehealth	11
Mobile Applications	2
Remote Patient Monitoring Systems	3
Biosurveillance	1

Digital Communications	2
Serologic Tests	1
Ventillators, its components, and its parameters	13
Contact Tracing	3
AI Tool / Machine Learning / IoT Models	8
Robots	3

As shown in Fig. 2, the chart demonstrates the distribution of technology strategies implemented across various Latin American countries during the COVID-19 pandemic, with Argentina, Brazil, and Colombia leading in the number of instances.

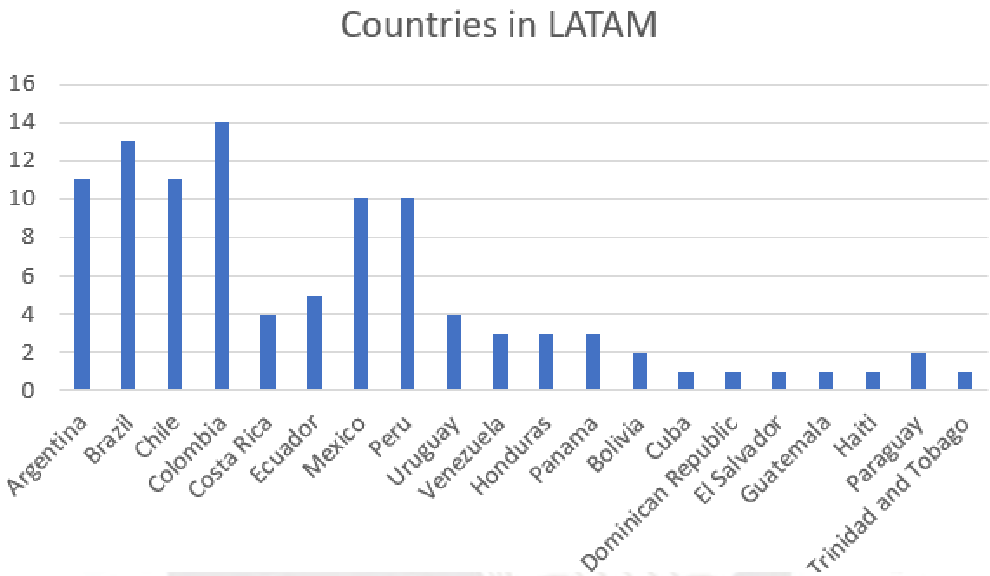

Figure 2: *Distribution of Technology Strategies Implemented in Latin American during the COVID-19 pandemic.*

3.2. Success rate of Technological Interventions

The success rates of the various technological interventions varied depending on the type of technology, country, and implementation context. Table 3 summarizes the success rates for the primary interventions analyzed in the reviewed studies.

Table 3: *Success Rates of Technological Interventions*

Technology / Intervention	Country	Success Rate
Telemedicine (Nieblas, Okoye, Carrión, Mehta, & Mehta, 2022)	Mexico, Colombia, Peru, Brazil, Chile, Argentina	70% positive outcomes, various specific successes in different countries.
Telemedicine, E-health Records, Biosurveillance, Consumer Empowerment Systems (Schwalb,	Brazil, Mexico, Colombia, Peru, Chile, Argentina	General success, specifics not quantified.

Armyra, Méndez-Aranda, & Ugarte-Gil, 2022)		
Telemedicine (Camacho-Leon et al., 2022)	Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Honduras, Mexico, Peru, Uruguay, Venezuela	High adoption and significant use, specific successes in different countries
Telemedicine Platforms, Videoconferencing Tools, Digital Platforms (Microsoft Teams®) (Libreros-Peña, Quintero, & Gelves, 2023)	Colombia	4652 teleconsultations recorded between April 2020 and February 2022, average waiting time approximately 2 hours.
Contact Tracing (Fernández-Niño, Peña-Maldonado, Rojas-Botero, & Rodriguez-Villamizar, 2021)	Colombia	Reduced fatality by 48%, prevented 1.8% of deaths
Contact Tracing, Testing Policies (Martinez-Valle, 2021)	Argentina, Brazil, Chile, Colombia, Mexico, Peru	Argentina and Peru maintained high contact tracing levels above 80%, while Colombia's rate dropped to 57%. Brazil and Mexico had less comprehensive tracing. Extensive testing in Colombia and Chile led to better pandemic management, lowering mortality rates early on.
Low-Cost Mechanical Ventilator (Giraldo-Cadavid et al., 2024)	Colombia	Effective, high usability, 98% measurements within desired criteria.
AI-Assisted Tool for Early Lung Cancer Detection and COVID-19 (Goncalves, Fong, & Blokhina, 2022)	Brazil, Mexico, Argentina, Chile, Colombia, Costa Rica, Panama	High accuracy (97%), sensitivity (64%), specificity (97%)
CODOP Machine Learning Model (Klén et al., 2022)	Argentina, Honduras, Bolivia	AUROC: 0.90–0.96, high sensitivity (78-100%) and specificity (48-67%)
Splitting Ventilator Valve (DA Silva et al., 2021)	Brazil	Promising initial results, specific success metrics not provided
Real-Time Stress Index Calculation Method (Caballero et al., 2022)	Brazil	Effective in simulations and prototype tests, specific success metrics not provided

Smart Healthcare System (Coelho Silva, Bianchi, Ribeiro, Sá Silva, & Oliveira, 2022)	Brazil, Portugal	High performance (quality factor 95-99%) under stress tests
Low-Cost CPAP Device (F. S. L., Urrutia, Freire, Jordán, Nuñez, & Pérez, 2022)	Ecuador	Effective in simulations and prototype tests, specific success metrics not provided
Developments included low-cost sensors for ventilators, a valve for sharing ventilators among patients, a full-face mask adapter for better PPE, biocide nanoparticles to enhance face masks, a deep learning system for real-time facemask detection, and drones for disinfecting large areas. (Hoff, Ponce, & Sossa, 2021)	Brazil, Mexico, Panama, Ecuador, Argentina	Positive preliminary findings, specific success rates not provided
Low-Cost Smartband (Lima Vieira, De Almeida Carlos, & Jose Irineu, 2021)	Brazil	82% success rate in identifying face-touch gestures
Rinku's Clinical Kit (Rodriguez et al., 2021)	Mexico	Successful communication and data collection, specific success rates not provided
Deep Learning Algorithm for X-ray Analysis (Alvarado-Díaz & Meneses-Claudio, 2021)	Peru	80% success rate in identifying COVID-19 cases
Machine Learning Models (Paiva de Oliveira, Bastos Filho, de Medeiros, dos Santos, & Lopes Freire, 2021)	Brazil	Over 99% accuracy in classifying test results, over 92% accuracy in predicting hospitalization needs
Deep Learning Algorithm with AlexNet (Cortés & Sánchez, 2021)	Mexico	96.5% accuracy, 98% sensitivity, 91.7% specificity
Clustering and Visualization Tool (Orjuela-Cañon & Perdomo, 2021)	Colombia	75% sensitivity, best cases 100%
Low-Cost Volume Sensors (Araujo Damasceno et al., 2021)	Brazil	IR sensor: 0.2% error, Pitot tube: 76.9% error, Venturi tube: 4.8% error

Telemedicine Platforms, Videoconferencing Tools, Digital Health Solutions, Mobile Health Applications (Saigí-Rubió, 2023)	Argentina, Bolivia, Chile, Colombia, Ecuador, Honduras, Mexico, Peru, Uruguay	Significant increase in adoption, specific numbers not provided
Mobile Manipulator Robot (Varela-Aldás, Buele, Guerrero-Núñez, & Andaluz, 2022)	Ecuador	Average system parameter qualification score of 4.63 out of 5
Telemedicine platforms, Telehealth systems, Point-of-care rapid testing (Alvarez-Moreno et al., 2024)	Brazil, Chile, Colombia, Mexico	Integration of technologies successful, specific success rates not provided
Telemedicine Platforms, Videoconferencing Tools, Telehealth Systems (Pinto et al., 2022)	Spain, Brazil, Colombia	Substantial increase in adoption, specific numbers not provided
COVID-Bot (Camacho, Ospina, & Calderón, 2021)	Colombia, USA	System effectiveness demonstrated, specific success metrics not provided
Mechanical Ventilators (Ventilador Mecánico Neyün) (Bugedo et al., 2022)	Chile	Out of 35 initiatives, 22 advanced to evaluation, and several passed trials. Five projects (Neyün-F, Asmar, Valdivia, Vemers-UC, B.AMBÚ-P1) received CORFO funding for mass production.
Disinfection and Cleaning Robots, Assistance, Service and Logistics Robots, Telemedicine and Telepresence Robots (Sierra Marín et al., 2021)	Colombia, Argentina, Chile, Brazil, United Kingdom	65.8% of clinicians recommended use of assistance, service, and logistics robots
3D Printing, Telemedicine and Telehealth, Robotics, AI and Big Data, Mobile Applications, EHR, Temperature Monitoring Devices (Bejarano, Navarro, & Marín García, 2021)	Colombia, China, United States, United Kingdom, Brazil, Argentina, Peru, Spain, Italy, Germany, South Korea, Israel, India	The article highlights successful implementations of new technologies, including 3D printing for medical supplies, the expansion of telemedicine for remote consultations, the deployment of robotics for disinfection and assistance, and the use of mobile applications for contact tracing and

		monitoring. Specific numbers not provided
PytuTester (Morales et al., 2022)	Paraguay, Peru, USA	Good accuracy in measuring flow profiles, specific metrics provided
Masi Ventilator (Gomez-Alzate, Perez-Buitrago, Cordova, Bornas, & Castaneda, 2021)	Peru	Met required tolerances for tidal volume and PIP, specific metrics provided
Testing and Tracking Technologies, Ventilators and ICU Beds (Benítez et al., 2020)	Brazil, Chile, Colombia, Ecuador, Peru	Varying success, specific metrics not provided
Masi Ventilator with NIV capabilities (Leiva et al., 2022)	Peru	Facial mask most effective accessory for NIV, specific metrics provided
Masi Mechanical Ventilator (Perez-Buitrago et al., 2021)	Peru	Errors below 15% tolerance after calibration, specific metrics provided
Hospital Websites and Digital Communication (Zavala, González, & Cornejo, 2022)	Brazil, Colombia, Chile	Not explicitly mentioned but highlights effective communication strategies in top-ranked hospitals.

3.3. Contribution of developed or implemented technology

The contributions of these technologies were significant in enhancing healthcare delivery, improving patient outcomes, and mitigating the impact of the pandemic. Table 4 outlines the specific contributions of the key technological interventions reviewed in this study.

Table 4: *Contributions of Technological Interventions*

Technology / Intervention	**Country**	**Contribution of Developed or Implemented Technology**
Telemedicine (Nieblas, Okoye, Carrión, Mehta, & Mehta, 2022)	Mexico, Colombia, Peru, Brazil, Chile, Argentina	Expanded access to healthcare, maintaining continuity of care during the pandemic.
Telemedicine, E-health Records, Biosurveillance, Consumer Empowerment Systems (Schwalb,	Brazil, Mexico, Colombia, Peru, Chile, Argentina	Improved healthcare delivery, monitoring, and patient empowerment.

Armyra, Méndez-Aranda, & Ugarte-Gil, 2022)		
Telemedicine (Camacho-Leon et al., 2022)	Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Honduras, Mexico, Peru, Uruguay, Venezuela	Enhanced healthcare access and efficiency.
Telemedicine Platforms, Videoconferencing Tools, Digital Platforms (Microsoft Teams®) (Libreros-Peña, Quintero, & Gelves, 2023)	Colombia	Provided continuity of care, reduced in-person visits, maintained healthcare access during the pandemic.
Contact Tracing (Fernández-Niño, Peña-Maldonado, Rojas-Botero, & Rodriguez-Villamizar, 2021)	Colombia	Reduced COVID-19 fatality rates, improved tracking of cases and contacts.
Contact Tracing, Testing Policies (Martinez-Valle, 2021)	Argentina, Brazil, Chile, Colombia, Mexico, Peru	Enhanced pandemic management through rigorous contact tracing and testing policies.
Low-Cost Mechanical Ventilator (Giraldo-Cadavid et al., 2024)	Colombia	Provided a cost-effective solution for ventilatory support during the pandemic.
AI-Assisted Tool for Early Lung Cancer Detection and COVID-19 (Goncalves, Fong, & Blokhina, 2022)	Brazil, Mexico, Argentina, Chile, Colombia, Costa Rica, Panama	Improved early detection of lung cancer and COVID-19, enhancing diagnostic accuracy and efficiency.
CODOP Machine Learning Model (Klén et al., 2022)	Argentina, Honduras, Bolivia	Aided in effective resource allocation in hospitals through accurate predictions of patient outcomes.
Splitting Ventilator Valve (DA Silva et al., 2021)	Brazil	Addressed ventilator shortages by enabling one ventilator to support multiple patients.

Real-Time Stress Index Calculation Method (Caballero et al., 2022)	Brazil	Enhanced ventilator performance and patient care by preventing ventilator-induced lung injury.
Smart Healthcare System (Coelho Silva, Bianchi, Ribeiro, Sá Silva, & Oliveira, 2022)	Brazil, Portugal	Improved healthcare management and patient monitoring through IoT and edge computing technologies.
Low-Cost CPAP Device (F. S. L., Urrutia, Freire, Jordán, Nuñez, & Pérez, 2022)	Ecuador	Provided a non-invasive, cost-effective solution for respiratory support.
Developments included low-cost sensors for ventilators, a valve for sharing ventilators among patients, a full-face mask adapter for better PPE, biocide nanoparticles to enhance face masks, a deep learning system for real-time facemask detection, and drones for disinfecting large areas (Hoff, Ponce, & Sossa, 2021)	Brazil, Mexico, Panama, Ecuador, Argentina	Enhanced PPE effectiveness, improved ventilation solutions, and provided real-time facemask detection and large area disinfection.
Low-Cost Smartband (Lima Vieira, De Almeida Carlos, & Jose Irineu, 2021)	Brazil	Assisted in preventing COVID-19 transmission by alerting users when they attempt to touch their face.
Rinku's Clinical Kit (Rodriguez et al., 2021)	Mexico	Provided real-time monitoring and data collection for COVID-19 symptoms, enhancing healthcare resource management.
Deep Learning Algorithm for X-ray Analysis	Peru	Improved diagnostic accuracy for COVID-19

(Alvarado-Díaz & Meneses-Claudio, 2021)		through advanced image analysis.
Machine Learning Models (Paiva de Oliveira, Bastos Filho, de Medeiros, dos Santos, & Lopes Freire, 2021)	Brazil	Provided accurate classification of COVID-19 test results and prediction of hospitalization needs, enhancing healthcare decision-making.
Deep Learning Algorithm with AlexNet (Cortés & Sánchez, 2021)	Mexico	Provided rapid and accurate diagnosis of COVID-19 from chest X-rays.
Clustering and Visualization Tool (Orjuela-Cañon & Perdomo, 2021)	Colombia	Aided in identifying high-risk groups and managing patient flow and resource allocation.
Low-Cost Volume Sensors (Araujo Damasceno et al., 2021)	Brazil	Offered affordable and effective solutions for mechanical ventilator volume measurement.
Telemedicine Platforms, Videoconferencing Tools, Digital Health Solutions, Mobile Health Applications (Saigí-Rubió, 2023)	Argentina, Bolivia, Chile, Colombia, Ecuador, Honduras, Mexico, Peru, Uruguay	Facilitated remote healthcare delivery, improving access and continuity of care during the pandemic.
Mobile Manipulator Robot (Varela-Aldás, Buele, Guerrero-Núñez, & Andaluz, 2022)	Ecuador	Reduced workload on hospital staff and minimized risk of infection by performing tasks such as delivering supplies.
Telemedicine platforms, Telehealth systems, Point-of-care rapid testing (Alvarez-Moreno et al., 2024)	Brazil, Chile, Colombia, Mexico	Enhanced diagnostic capabilities and patient outcomes through integrated telemedicine and rapid testing technologies.
Telemedicine Platforms, Videoconferencing Tools, Telehealth Systems (Pinto et al., 2022)	Spain, Brazil, Colombia	Facilitated remote healthcare delivery, managing healthcare remotely and effectively.

COVID-Bot (Camacho, Ospina, & Calderón, 2021)	Colombia, USA	Provided effective autonomous disinfection solutions for indoor environments.
Mechanical Ventilators (Ventilador Mecánico Neyün) (Bugedo et al., 2022)	Chile	Addressed ventilator shortages with effective solutions, several prototypes passed trials and received funding for mass production.
Disinfection and Cleaning Robots, Assistance, Service and Logistics Robots, Telemedicine and Telepresence Robots (Sierra Marín et al., 2021)	Colombia, Argentina, Chile, Brazil, United Kingdom	Enhanced healthcare operations and reduced infection risk through various robotic applications.
3D Printing, Telemedicine and Telehealth, Robotics, AI and Big Data, Mobile Applications, EHR, Temperature Monitoring Devices (Bejarano, Navarro, & Marín García, 2021)	Colombia, China, United States, United Kingdom, Brazil, Argentina, Peru, Spain, Italy, Germany, South Korea, Israel, India	Enabled the rapid production of medical supplies, expanded remote consultations, and improved healthcare management and monitoring.
PytuTester (Morales et al., 2022)	Paraguay, Peru, USA	Provided an accurate, low-cost solution for testing and verifying ventilator performance.
Masi Ventilator (Gomez-Alzate, Perez-Buitrago, Cordova, Bornas, & Castaneda, 2021)	Peru	Met required tolerances for ventilatory parameters, providing effective respiratory support.
Testing and Tracking Technologies, Ventilators and ICU Beds (Benítez et al., 2020)	Brazil, Chile, Colombia, Ecuador, Peru	Enhanced pandemic response through improved testing, tracking, and critical care infrastructure.
Masi Ventilator with NIV capabilities (Leiva et al., 2022)	Peru	Improved non-invasive ventilation options for patients with respiratory failure.

Masi Mechanical Ventilator (Perez-Buitrago et al., 2021)	Peru	Provided reliable ventilatory support even at high altitudes, with performance within acceptable error margins.
Hospital Websites and Digital Communication (Zavala, González, & Cornejo, 2022)	Brazil, Colombia, Chile	Highlighted effective digital communication strategies in top-ranked hospitals.

3.4. Technology Readiness Level (TRL) maturity

The TRL of the technologies reviewed varied from early prototype stages to full operational deployment. Table 5 summarizes the TRL levels for each of the interventions, indicating their readiness for widespread implementation.

Table 5: *TRL Maturity of Technological Interventions*

Technology / Intervention	Country	TRL Maturity
Telemedicine (Nieblas, Okoye, Carrión, Mehta, & Mehta, 2022)	Mexico, Colombia, Peru, Brazil, Chile, Argentina	TRL 9: Actual system proven in operational environment
Telemedicine, E-health Records, Biosurveillance, Consumer Empowerment Systems (Schwalb, Armyra, Méndez-Aranda, & Ugarte-Gil, 2022)	Brazil, Mexico, Colombia, Peru, Chile, Argentina	TRL 9: Actual system proven in operational environment
Telemedicine (Camacho-Leon et al., 2022)	Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Honduras, Mexico, Peru, Uruguay, Venezuela	TRL 9: Actual system proven in operational environment
Telemedicine Platforms, Videoconferencing Tools, Digital Platforms (Microsoft Teams®) (Libreros-Peña, Quintero, & Gelves, 2023)	Colombia	TRL 9: Actual system proven in operational environment
Contact Tracing (Fernández-Niño, Peña-Maldonado, Rojas-Botero, & Rodriguez-Villamizar, 2021)	Colombia	TRL 8-9: System complete and qualified, proven in operational environment
Contact Tracing, Testing Policies (Martinez-Valle, 2021)	Argentina, Brazil, Chile, Colombia, Mexico, Peru	TRL 8-9: System complete and qualified, proven in operational environment

Low-Cost Mechanical Ventilator (Giraldo-Cadavid et al., 2024)	Colombia	TRL 8: System complete and qualified
AI-Assisted Tool for Early Lung Cancer Detection and COVID-19 (Goncalves, Fong, & Blokhina, 2022)	Brazil, Mexico, Argentina, Chile, Colombia, Costa Rica, Panama	TRL 7-8: System prototype demonstrated in operational environment, nearing completion
CODOP Machine Learning Model (Klén et al., 2022)	Argentina, Honduras, Bolivia	TRL 6-7: Technology demonstrated in relevant environment, system prototype in operational environment
Splitting Ventilator Valve (DA Silva et al., 2021)	Brazil	TRL 6-7: Technology demonstrated in relevant environment, system prototype in operational environment
Real-Time Stress Index Calculation Method (Caballero et al., 2022)	Brazil	TRL 6: Technology demonstrated in relevant environment
Smart Healthcare System (Coelho Silva, Bianchi, Ribeiro, Sá Silva, & Oliveira, 2022)	Brazil, Portugal	TRL 6: Technology demonstrated in relevant environment
Low-Cost CPAP Device (F. S. L., Urrutia, Freire, Jordán, Nuñez, & Pérez, 2022)	Ecuador	TRL 6: Technology demonstrated in relevant environment
Developments included low-cost sensors for ventilators, a valve for sharing ventilators among patients, a full-face mask adapter for better PPE, biocide nanoparticles to enhance face masks, a deep learning system for real-time facemask detection, and drones for disinfecting large areas (Hoff, Ponce, & Sossa, 2021)	Brazil, Mexico, Panama, Ecuador, Argentina	TRL 6-7: Technology demonstrated in relevant environment, system prototype in operational environment
Low-Cost Smartband (Lima Vieira, De Almeida Carlos, & Jose Irineu, 2021)	Brazil	TRL 7: System prototype demonstration in operational environment
Rinku's Clinical Kit (Rodriguez et al., 2021)	Mexico	TRL 7: System prototype demonstration in operational environment

Deep Learning Algorithm for X-ray Analysis (Alvarado-Díaz & Meneses-Claudio, 2021)	Peru	TRL 7: System prototype demonstration in operational environment
Machine Learning Models (Paiva de Oliveira, Bastos Filho, de Medeiros, dos Santos, & Lopes Freire, 2021)	Brazil	TRL 7: System prototype demonstration in operational environment
Deep Learning Algorithm with AlexNet (Cortés & Sánchez, 2021)	Mexico	TRL 7: System prototype demonstration in operational environment
Clustering and Visualization Tool (Orjuela-Cañon & Perdomo, 2021)	Colombia	TRL 7: System prototype demonstration in operational environment
Low-Cost Volume Sensors (Araujo Damasceno et al., 2021)	Brazil	TRL 7: System prototype demonstration in operational environment
Telemedicine Platforms, Videoconferencing Tools, Digital Health Solutions, Mobile Health Applications (Saigí-Rubió, 2023)	Argentina, Bolivia, Chile, Colombia, Ecuador, Honduras, Mexico, Peru, Uruguay	TRL 9: Actual system proven in operational environment
Mobile Manipulator Robot (Varela-Aldás, Buele, Guerrero-Núñez, & Andaluz, 2022)	Ecuador	TRL 7-8: System prototype demonstrated in operational environment, nearing completion
Telemedicine platforms, Telehealth systems, Point-of-care rapid testing (Alvarez-Moreno et al., 2024)	Brazil, Chile, Colombia, Mexico	TRL 8-9: System complete and qualified, proven in operational environment
Telemedicine Platforms, Videoconferencing Tools, Telehealth Systems (Pinto et al., 2022)	Spain, Brazil, Colombia	TRL 9: Actual system proven in operational environment
COVID-Bot (Camacho, Ospina, & Calderón, 2021)	Colombia, USA	TRL 7-8: System prototype demonstrated in operational environment, nearing completion
Mechanical Ventilators (Ventilador Mecánico Neyün) (Bugedo et al., 2022)	Chile	TRL 7-8: System prototype demonstrated in operational environment, nearing completion
Disinfection and Cleaning Robots, Assistance, Service and Logistics	Colombia, Argentina, Chile, Brazil, United Kingdom	TRL 6-7: Technology demonstrated in relevant environment, system

Robots, Telemedicine and Telepresence Robots (Sierra Marín et al., 2021)		prototype in operational environment
3D Printing, Telemedicine and Telehealth, Robotics, AI and Big Data, Mobile Applications, EHR, Temperature Monitoring Devices (Bejarano, Navarro, & Marín García, 2021)	Colombia, China, United States, United Kingdom, Brazil, Argentina, Peru, Spain, Italy, Germany, South Korea, Israel, India	TRL 7-9: Technology demonstrated in operational environment, nearing completion, proven in operational environment
PytuTester (Morales et al., 2022)	Paraguay, Peru, USA	TRL 7-8: System prototype demonstrated in operational environment, nearing completion
Masi Ventilator (Gomez-Alzate, Perez-Buitrago, Cordova, Bornas, & Castaneda, 2021)	Peru	TRL 7-8: System prototype demonstrated in operational environment, nearing completion
Testing and Tracking Technologies, Ventilators and ICU Beds (Benítez et al., 2020)	Brazil, Chile, Colombia, Ecuador, Peru	TRL 7-8: Technology demonstrated in relevant environment, system prototype in operational environment
Masi Ventilator with NIV capabilities (Leiva et al., 2022)	Peru	TRL 7-8: System prototype demonstrated in operational environment, nearing completion
Masi Mechanical Ventilator (Perez-Buitrago et al., 2021)	Peru	TRL 8-9: System complete and qualified, proven in operational environment
Hospital Websites and Digital Communication (Zavala, González, & Cornejo, 2022)	Brazil, Colombia, Chile	Not explicitly mentioned but highlights effective communication strategies

Chapter IV: Discussion

This chapter discusses the findings from the systematic review of technological interventions implemented in Latin America during the COVID-19 pandemic, providing a comprehensive view of their success, contributions, and challenges. The diverse set of interventions, including telemedicine, artificial intelligence (AI) tools, low-cost ventilators, and mobile health applications, underscores the region's rapid and innovative response to the pandemic's unique challenges.

4.1. Adoption and Success Rates of Technological Interventions

The adoption of these technologies varied significantly across different countries and settings, influenced by infrastructure, government support, and public acceptance. Telemedicine, for instance, was highly successful and widely adopted in countries such as Mexico, Colombia, Peru, Brazil, Chile, and Argentina. The success rate, as indicated by positive patient outcomes and high usage, was around 70%, demonstrating telemedicine's critical role in maintaining healthcare continuity during lockdowns and periods of high infection rates (Tejedor, Pérez-Escoda, Ventín, Tusa, & Martínez, 2020).

Other technologies, such as contact tracing systems, had varying levels of success. In countries like Colombia and Argentina, robust contact tracing led to a significant reduction in COVID-19 fatality rates and improved management of outbreaks. By contrast, Brazil and Mexico faced challenges in maintaining comprehensive contact tracing, which resulted in less effective pandemic control.
Low-cost mechanical ventilators, such as the Masi Ventilator developed in Peru, and the Unisabana-HERONS ventilator in Colombia, were successfully implemented, meeting necessary performance criteria and providing affordable alternatives for respiratory support. These solutions addressed the ventilator shortage during peak periods of the pandemic and were crucial in saving lives in resource-constrained environments.

Additionally, AI-assisted diagnostic tools demonstrated high levels of accuracy and specificity, improving the early detection of COVID-19 and other respiratory conditions. For instance, Brazil's AI tools for early lung cancer detection achieved a 97% accuracy rate, showcasing the potential of AI in enhancing diagnostic capabilities, even in low-resource settings (Goncalves, Fong, & Blokhina, 2022).

4.2. Contributions to Healthcare Delivery and Patient Outcomes

The reviewed interventions contributed significantly to enhancing healthcare delivery, improving patient outcomes, and mitigating the pandemic's impact. The integration of telemedicine and remote patient monitoring systems ensured that healthcare services remained accessible, reducing the burden on hospitals and healthcare workers. In addition, contact tracing technologies played a vital role in tracking and managing outbreaks, while mobile health applications facilitated patient engagement and self-monitoring.

Technological innovations such as low-cost mechanical ventilators and remote patient monitoring systems provided critical support during the pandemic's peak, particularly in countries with limited healthcare resources. The Masi Ventilator in Peru and the Unisabana-HERONS Ventilator in Colombia were pivotal in addressing ventilator shortages, providing respiratory support for COVID-19 patients.

The deployment of AI and machine learning models contributed to the management of patient flow and resource allocation, aiding in clinical decision-making. These tools not only enhanced diagnostic accuracy but also supported healthcare providers in predicting patient outcomes and optimizing resource use.

4.3. Challenges and Barriers to Implementation

Despite the positive outcomes, the implementation of these technologies faced numerous challenges and barriers. Limited infrastructure, particularly in rural and underserved regions, hindered the widespread adoption of telemedicine and remote care systems. In many areas, a lack of access to high-speed internet and digital devices limited the reach of these interventions, creating disparities in healthcare access.

Regulatory challenges and a lack of standardized guidelines for the deployment of emerging technologies, such as AI tools and low-cost ventilators, also impeded the scale-up and integration of these innovations. In some cases, the absence of clear regulatory pathways delayed the approval and deployment of potentially life-saving technologies.

Additionally, the rapid pace of implementation, driven by the urgency of the pandemic, sometimes led to suboptimal integration into existing healthcare systems. This situation resulted in fragmented services and reduced the long-term sustainability of these interventions.

4.4. Technology Readiness Levels and Sustainability

The Technology Readiness Levels (TRLs) of the reviewed technologies varied widely, reflecting different stages of maturity and readiness for deployment. Many telemedicine platforms achieved TRL 9, indicating full operational deployment in real-world settings during the pandemic. However, the sustainability of these platforms beyond the pandemic remains uncertain due to insufficient evidence of continued use and integration into regular healthcare systems.

Similarly, contact tracing technologies reached TRL 8-9, demonstrating complete system readiness and operational qualification. Yet, the lack of post-pandemic data on their continued application raises concerns about their long-term sustainability.

Additionally, low-cost mechanical ventilators and other innovative medical devices demonstrated effective prototypes at TRL 7-8, but clear pathways for mass production and regular use beyond the pandemic’s peak have yet to be established, limiting their broader impact on healthcare systems.
Other interventions, such as AI tools and machine learning models, achieved TRL 6-8, indicating that while these technologies were operational during the pandemic, their long-term adoption and application in healthcare settings are still limited.

Conclusions

The COVID-19 pandemic catalyzed significant technological advancements in Latin America, showcasing the region's capability to innovate under crisis conditions. The systematic review highlights the effectiveness of various technologies in mitigating the impact of the pandemic, improving patient outcomes, and ensuring the continuity of healthcare services. However, the success of these interventions was contingent on several factors, including infrastructure, government support, and public acceptance.

A critical finding from the review is that most of these technologies lack information regarding their continuity or subsequent use. Despite the initial high Technology Readiness Levels (TRLs) indicating operational or near-operational status for many interventions, there is limited data on whether these technologies have been sustained or integrated into regular healthcare practices post-pandemic. For instance:

a. Telemedicine platforms achieved TRL 9, indicating full operational deployment during the pandemic, yet there is little evidence of their continued use or long-term integration into healthcare systems.

b. Contact tracing technologies reached TRL 8-9, showing they were complete and qualified for use. However, the absence of reports on their ongoing application raises concerns about their sustainability.

c. Low-cost mechanical ventilators and other innovative medical devices, while demonstrating effective prototypes (TRL 7-8), have not shown clear pathways for mass production or regular use beyond the pandemic's peak.

d. AI tools and machine learning models also reached advanced TRL stages (TRL 6-8), but their long-term adoption and continuous application in healthcare settings remain uncertain.

The lack of continuity highlights a significant gap between the development and sustained utilization of these technologies. It underscores the need for stronger policies and frameworks to ensure the long-term integration and scalability of technological interventions in healthcare systems.

Governments in Latin America need to prioritize funding for technology continuity, streamline regulatory processes, and foster collaborations between public and private sectors to ensure that these innovations are not just temporary solutions but become permanent fixtures in the healthcare landscape.

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