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Review

Current Advancements in Drone Technology for Medical Sample Transportation

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Abstract: *Background:* The integration of drone technology into healthcare logistics presents a significant opportunity to enhance the speed, reliability, and efficiency of medical sample transportation. *Methods:* This paper provides a narrative review of current advancements in drone technology, focusing on its application in the rapid and secure delivery of medical samples, particularly in urban and remote regions where traditional transportation methods often face challenges. Drawing from recent studies and case reports, the review highlights the role of technologies such as artificial intelligence (AI)-driven navigation systems, real-time monitoring, and secure payload management in mitigating logistical barriers like traffic congestion and geographical isolation. *Results:* Based on findings from various case studies, the review demonstrates how drones can significantly reduce transportation time and costs, while improving accessibility to healthcare services in underserved areas. *Conclusions:* This paper concludes that, while challenges such as regulatory hurdles and privacy concerns remain, ongoing technological advancements and the development of supportive regulatory frameworks have the potential to revolutionize medical logistics, ultimately improving patient outcomes and healthcare delivery.

Keywords: drone technology; medical logistics; healthcare delivery; UAVs; medical sample transportation; healthcare innovation; AI-driven navigation; rural healthcare

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1. Introduction

The timely and secure transportation of medical samples, including blood, tissue, and diagnostic specimens, is critical to ensuring accurate diagnosis and prompt treatment [1–4]. The effectiveness of healthcare delivery often hinges on the speed and reliability of transporting these samples from collection points to laboratories or healthcare facilities [5,6]. However, traditional transportation methods—relying on ground vehicles—frequently encounter significant challenges. These include traffic congestion in urban areas, geographical barriers in rural or remote regions, and various logistical delays that can compromise the integrity and timeliness of sample delivery [7–9].

Unmanned aerial vehicles (UAVs), commonly known as drones, have emerged as a promising solution to these logistical challenges. Drones offer the ability to bypass ground-based obstacles by taking the most direct routes, significantly reducing transportation times and mitigating risks associated with delays [10–14]. Additionally, their ability to operate in a wide range of environments—from densely populated urban centers to isolated rural areas—makes them an adaptable and versatile option for medical logistics [15].

The aim of this narrative review is to examine the current advancements in drone technology, with a particular focus on its application in healthcare logistics. This review highlights recent developments in key areas such as AI-powered navigation systems, real-time monitoring, and secure payload management, which allow drones to operate more autonomously, navigating complex environments while ensuring the security and integrity of medical samples during transit [10,14,15].

Several case studies have demonstrated the potential of drones to overcome logistical challenges. For example, in Rwanda and Ghana, drone services have been successfully deployed to deliver critical medical supplies to remote and underserved regions, significantly reducing transportation time and improving access to healthcare services [7,10]. These examples illustrate the tangible benefits of drone technology, including reduced travel time and cost-effectiveness, which are crucial for improving patient outcomes and healthcare delivery.

Despite these advancements, the integration of drones into healthcare logistics is not without its challenges. Regulatory hurdles, privacy concerns, and the need for standardized protocols continue to pose barriers to widespread adoption. Understanding and addressing these challenges is crucial to ensure that drones can be scaled and sustainably integrated into existing healthcare infrastructure [15].

This paper contributes to the growing body of literature by providing a comprehensive review of the existing research and case studies on drone-based medical transportation. It synthesizes the findings from various studies, critically examining the role of drone technology in healthcare logistics while identifying the key challenges and opportunities for future development. The novelty of this review lies in its detailed examination of how drones are being used in real-world scenarios, particularly in the context of medical sample transportation in underserved and geographically challenging areas. Additionally, the review identifies research gaps in current studies, offering insights into areas where further exploration is needed to fully realize the potential of drones in healthcare logistics.

2. Methodology

This paper adopts a narrative review methodology, aimed at synthesizing the latest advancements in drone technology as applied to medical sample transportation. The review focuses on studies that provide insights into both the technological developments and the practical implementation of drones in healthcare logistics. The selection of studies was guided by specific criteria to ensure a comprehensive analysis of the relevant literature.

2.1. Literature Search and Selection

To ensure a comprehensive and focused review, a systematic literature search was conducted across multiple databases, including PubMed, Google Scholar, and Scopus. The search strategy involved using specific keywords such as "drone technology", "medical sample transportation", "healthcare logistics", "AI-powered drones", and "unmanned aerial vehicles in healthcare". Studies published within the last 10 years were prioritized to ensure the inclusion of recent advancements in the field. The selection process, visualized in Figure 1, included both peer-reviewed journal articles and case studies to present a balanced view of academic research and practical applications.

The inclusion criteria were based on the relevance of studies to the primary focus areas: speed and efficiency of drone operations; accessibility in remote and underserved areas; regulatory challenges; and key technological innovations, such as AI-driven navigation systems; real-time monitoring; and secure payload management. Priority was given to studies that provided quantitative data or detailed case reports highlighting the practical application of drones in healthcare logistics. Studies outside the scope of healthcare logistics or those focusing solely on non-healthcare applications of drones were excluded.

Additionally, a thematic analysis was employed to categorize the selected studies into key themes, such as operational efficiency, regulatory hurdles, cost-effectiveness, and sustainability. This process is also reflected in Figure 1, which shows the number of studies identified, screened, and finally synthesized for analysis. This approach allowed for a comparative analysis of the various regions and case studies, identifying both benefits and challenges. The overall aim was to draw meaningful conclusions that can inform future research and the practical implementation of drone technology in healthcare.

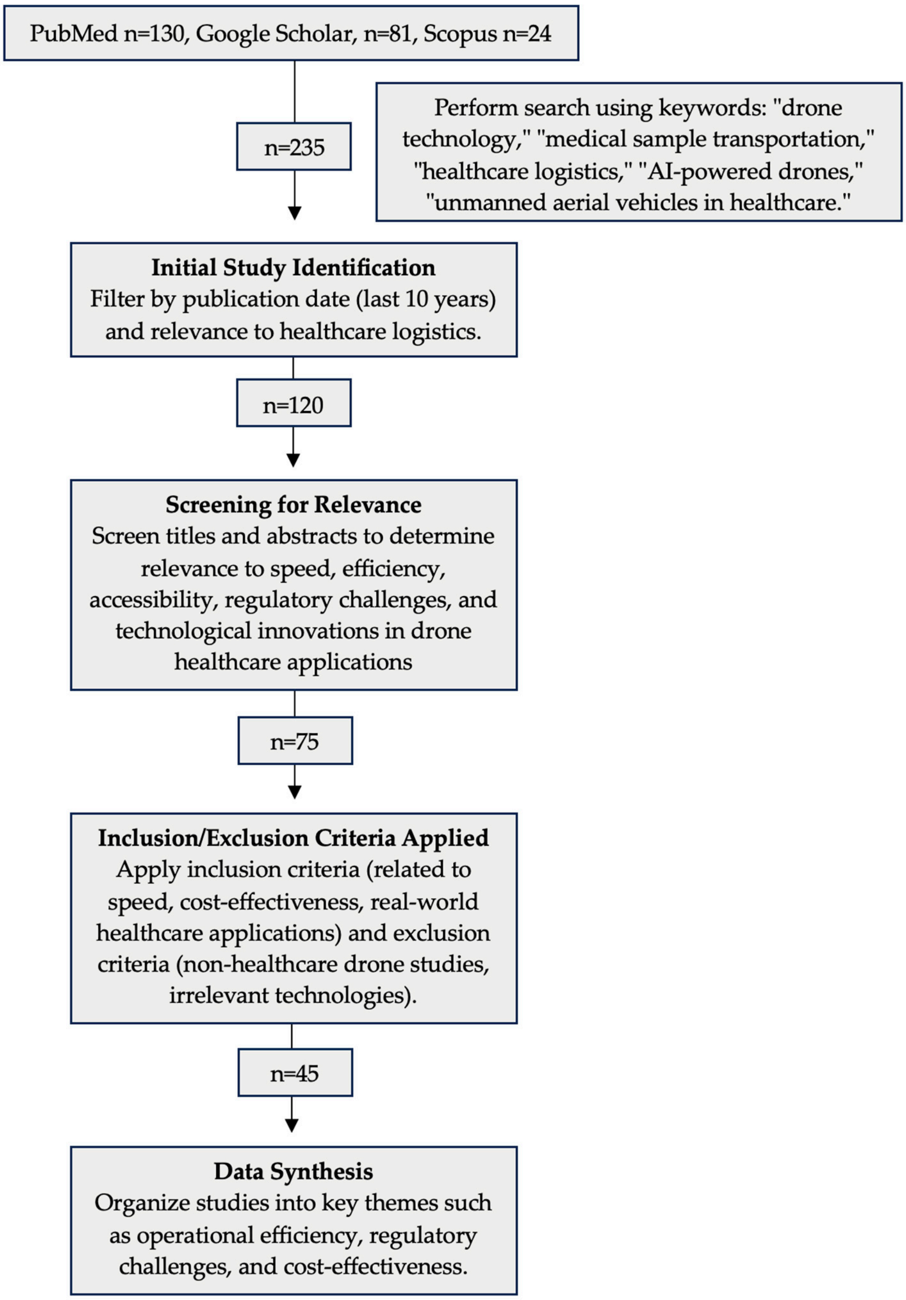

Figure 1. Flowchart of the literature search and selection process, starting with 235 studies from PubMed, Google Scholar, and Scopus. After screening and applying inclusion/exclusion criteria, 45 studies were selected and synthesized for thematic analysis.

2.2. Data Synthesis

The selected studies were analyzed and categorized into key themes, such as operational efficiency, cost-effectiveness, regulatory hurdles, and environmental sustainability. This thematic approach allowed us to draw comparisons between different case studies, highlighting both the benefits and challenges of drone implementation in healthcare logistics. In addition, the review identifies key research gaps in the literature, such as the need for more comprehensive regulatory frameworks and the integration of drones with existing healthcare systems.

Rather than simply summarizing the findings of the reviewed studies, this review offers a critical analysis of how drone technology has been applied in various healthcare settings. By identifying common challenges and opportunities across different regions and healthcare systems, the review contributes to the broader discussion on how drones can be effectively scaled and adopted in the medical sector.

2.3. Critical Discussion

The narrative review methodology allowed for a detailed examination of both qualitative and quantitative findings from the literature. Each selected study was evaluated for its contribution to understanding the potential of drones in overcoming logistical challenges such as geographic barriers, traffic congestion, and regulatory limitations. Case studies, such as the use of drones in Rwanda and Ghana, were analyzed for their practical outcomes, such as reduced transportation times and improved healthcare accessibility in remote areas.

The review also incorporates a critical discussion of technological advancements—for instance, the role of AI-driven systems and real-time monitoring in improving the reliability of drone operations. In doing so, the review identifies where further research is required, particularly in the areas of drone scalability and regulatory frameworks.

3. Speed and Efficiency

The adoption of drones for medical sample transportation is primarily driven by the need for speed and efficiency. Traditional methods of transporting medical samples, such as ground vehicles or couriers, often face significant delays due to traffic congestion, geographical barriers, and logistical challenges [7–9,16]. Drones offer a transformative solution to these problems by providing rapid and direct transportation, which is crucial for time-sensitive medical diagnostics and treatments [4,8,13].

3.1. Reduction in Transportation Time

The implementation of drone technology in medical sample transportation has brought about a significant reduction in delivery times, especially in urban areas where traffic congestion is a persistent issue, and in remote regions with challenging accessibility [17–20]. Traditional ground transportation methods are often subject to delays caused by traffic, road conditions, and the inherent inefficiencies of navigating urban landscapes. Drones, however, can fly directly from point A to point B, bypassing these obstacles and significantly shortening delivery times.

A study by Amukele et al. (2016) [17] demonstrated the effectiveness of drones in reducing transportation time for medical samples. In urban settings with heavy traffic, the average time required to transport samples by ground vehicles was approximately 38 min. In contrast, when using drones, this time was reduced to just 14 min. This substantial reduction in time can have critical implications for patient care, particularly in scenarios where every minute counts, such as in the transportation of blood samples for transfusions, organs for transplants, or time-sensitive diagnostic specimens [21,22].

3.2. Efficiency in Rural and Remote Areas

In rural and remote areas, where infrastructure is often underdeveloped or non-existent, drones provide an effective means of transportation. Ground transportation in these areas can be slow and unreliable due to poor road conditions and long distances between healthcare facilities [23,24]. Recent studies, such as those conducted by Haidari et al. (2016) [25] and Amukele et al. (2015) [26], have shown that drones can reduce transportation time by more than 50% compared to traditional methods, significantly improving the speed of medical diagnostics and patient care in these challenging environments. Drones can overcome these challenges by flying directly to remote clinics and hospitals, ensuring that medical samples are transported quickly and efficiently. This is particularly important in regions where timely medical diagnostics are critical for patient outcomes [17,27].

3.3. Increased Frequency of Sample Transportation

The speed and efficiency of drones also allow for more frequent transportation of medical samples. Traditional methods might only enable a limited number of sample collections per day due to logistical constraints [28,29]. In contrast, drones can make multiple trips in a day, ensuring that medical samples are transported as soon as they are collected. This increased frequency reduces the turnaround time for diagnostic results, enabling faster clinical decision-making and treatment initiation [26].

3.4. Operational Efficiency and Cost Savings

Drones not only enhance the speed of medical sample transportation but also improve operational efficiency and cost savings. The automation and direct routing capabilities of drones reduce the reliance on human couriers and ground vehicles, which can be expensive and less efficient [25]. The operational cost of drones, including maintenance and energy consumption, is generally lower compared to traditional transportation methods. This efficiency translates to cost savings for healthcare facilities, enabling them to allocate resources more effectively [5,6,30,31] (Table 1).

Table 1. Benefits of Using Drones in Medical Sample Transportation.

Benefit	Description
Speed	Significantly reduces transportation time
Efficiency	Enables direct routes, avoiding traffic and geographical barriers
Accessibility	Reaches remote and underserved areas
Cost-Effectiveness	Lowers transportation costs by reducing the need for ground vehicles
Reliability	Ensures sample integrity with advanced monitoring and secure payloads

3.5. Drone Flight Time and Payload Capacity

The flight time and payload capacity of drones used for medical logistics vary significantly depending on several factors, particularly the weight of the cargo. Generally, drones can stay airborne for anywhere between 15 min to over an hour, depending on their design, battery capacity, and payload. For instance, lighter drones with smaller payloads tend to have longer flight times, whereas drones carrying heavier medical supplies or diagnostic samples experience a reduction in both flight time and range.

Payload capacity also depends on the drone model and intended application. Many medical drones can carry up to 2–5 kg of cargo, but some advanced models can transport up to 10 kg over shorter distances [25,27]. Drones designed for longer distances, particularly in remote or hard-to-reach areas, often trade off payload capacity to maintain a more extended flight time. For example, the study by Otto and Williams (2020) [27] demonstrated that larger payloads significantly reduce the flight time, highlighting the importance of balancing cargo weight with operational efficiency.

4. Cost-Effectiveness

The integration of drones into healthcare logistics offers significant potential for cost savings across multiple dimensions, particularly when compared to traditional ground-based transportation methods [32]. Cost-effectiveness is one of the key drivers for the adoption of drone technology, especially in regions where healthcare budgets are constrained and operational efficiency is critical. This section explores the various ways in which drones contribute to cost reduction, including direct transportation costs, reduced reliance on human resources, and broader economic impacts resulting from faster healthcare delivery [5,33,34].

4.1. Direct Transportation Cost Savings

The primary cost savings associated with drones come from the reduction in direct transportation expenses [25,28]. Traditional ground transportation methods, such as the use of courier services, ambulances, or specialized medical transport vehicles, incur significant operational costs. These costs include fuel, vehicle maintenance, insurance, and the wages of drivers and supporting staff. For example, the cost of operating a ground vehicle can range from $0.60 to $2.50 per mile depending on the vehicle type, fuel costs, and maintenance expenses [5,25,28,35]. In contrast, drones—particularly electric models—have substantially lower operational costs, as they do not rely on fossil fuels and have minimal maintenance requirements.

Studies have shown that drones can reduce transportation costs by up to 50% compared to traditional methods, particularly in regions where terrain or infrastructure complicates ground transportation [25,26]. A report by Otto and Williams (2020) [27] highlighted that the cost per delivery when using drones in remote areas was approximately $0.88, compared to $2.22 for traditional methods. These savings are even more pronounced in regions with challenging terrains, where road maintenance is a significant expense and vehicles require frequent repairs (Table 2).

Table 2. Comparison of Transportation Time and Costs Between Drones and Ground Vehicles [25,27].

Environment	Transportation Method	Average Time (Minutes)	Average Cost per Delivery
Urban (High Traffic)	Ground Vehicle	38	$2.22
Urban (High Traffic)	Drone	14	$0.88
Rural/Remote	Ground Vehicle	60+	$3.00
Rural/Remote	Drone	25	$1.20

4.2. Labor Cost Reduction

Another significant cost-saving factor is the reduction in labor costs. Traditional medical sample transportation requires skilled drivers and support personnel, whose wages contribute significantly to the overall cost of transportation. Drones, being autonomous or remotely piloted, eliminate the need for drivers, reducing the associated labor costs [25]. This is particularly beneficial in high-cost regions where wages are a significant component of the transportation budget.

Furthermore, the automation of drone operations reduces the need for extensive logistical planning and coordination, as drones can be programmed to follow pre-determined routes with minimal human intervention [36–38]. This streamlining of operations not only reduces the need for a large workforce but also minimizes the potential for human error, further enhancing the cost-effectiveness of drone-based transportation [6,25].

4.3. Reduced Infrastructure Costs

Drones also help reduce infrastructure-related costs, which are a major component of traditional transportation systems. Ground transportation relies heavily on well-maintained roads, bridges, and traffic management systems, all of which require substantial investment from local and national governments. In contrast, drones operate in the airspace, avoiding the need for expensive infrastructure maintenance. This is particularly advantageous in rural and remote areas, where the cost of building and maintaining roads can be prohibitively expensive [39–41].

Moreover, drones can reach areas that are inaccessible by road, such as islands, mountainous regions, or areas affected by natural disasters, without the need for additional infrastructure investment. This ability to bypass the limitations of ground infrastructure makes drones an economically viable option for healthcare delivery in challenging environments.

4.4. Faster Turnaround Times and Economic Impact

One of the less immediately apparent but highly significant cost savings comes from the economic impact of faster turnaround times in healthcare delivery. Drones' ability to quickly transport medical samples and supplies can lead to faster diagnoses, earlier treatment initiation, and shorter hospital stays. This can have a profound impact on the overall cost of healthcare [18,24,40].

For instance, in emergency situations where time is critical, such as in the transport of blood for transfusions or organs for transplantation, the speed of drone delivery can save lives, reduce the length of hospital stays, and decrease the need for expensive critical care services [41]. By reducing the time from diagnosis to treatment, drones can help lower the costs associated with prolonged hospital admissions, unnecessary diagnostic procedures, and the escalation of patient conditions that result from delays in receiving appropriate care [42,43].

A study conducted by the World Bank on the use of drones in healthcare logistics in sub-Saharan Africa found that the reduction in transportation time led to a decrease in overall healthcare costs by as much as 25% [44]. This reduction was primarily due to faster diagnostic processes, which enabled healthcare providers to initiate treatment earlier, thereby reducing the severity of patient conditions and the need for extended hospital stays.

4.5. Scalability and Cost Efficiency

The widespread adoption of drone-based medical sample transportation has the potential to generate significant economic benefits beyond immediate cost savings. One of the primary advantages of drone implementation is the reduction in transportation costs, which has been demonstrated by various studies showing up to 50% cost savings compared to traditional ground-based methods [27]. These savings allow healthcare providers to allocate more resources to patient care and expand their services, particularly in underserved areas.

In addition to direct cost reductions, drone adoption can stimulate job creation in several sectors. While drones reduce the need for drivers in traditional transportation, new jobs will emerge in areas such as drone operation, maintenance, software development, and logistics management. As drone networks expand, the need for skilled technicians and operators will increase, providing economic opportunities in both urban and rural areas. Furthermore, the growth of drone technology can foster innovation in related industries, such as battery technology and autonomous systems, contributing to broader economic growth.

The improvement in healthcare access is another major economic benefit of drone adoption. By enabling faster and more reliable transportation of medical samples, drones can significantly reduce delays in diagnosis and treatment, which in turn leads to better health outcomes and lower long-term healthcare costs. This improvement is especially critical in remote or underserved regions, where traditional transportation methods are either slow or unreliable. The ability of drones to bypass geographical barriers and provide timely medical deliveries ensures that healthcare services reach a broader population, ultimately improving public health and reducing the economic burden of untreated or delayed medical conditions.

Overall, the widespread adoption of drones in healthcare logistics will not only reduce operational costs but also contribute to job creation, foster technological innovation, and improve access to essential healthcare services, all of which have a positive long-term economic impact.

4.6. Quantitative Impact on Healthcare Delivery

The integration of drones into medical sample transportation has led to measurable improvements in healthcare delivery, particularly in terms of reducing delivery times and enhancing the efficiency of diagnostic processes. Quantitative data from several case studies highlight the transformative effects of drone-based transportation in both urban and rural healthcare systems.

One of the key advantages of drone technology is the substantial reduction in transportation time. For example, a study by Amukele et al. (2016) found that in congested urban environments, drones reduced medical sample delivery time from an average of 38 min by ground vehicles to 14 min using UAVs [17]. This represents a 63% reduction in delivery time, which can be critical for time-sensitive diagnostics such as blood tests or organ transplants. Similar studies in rural settings have demonstrated even greater time savings. Haidari et al. (2016) observed that drone-based transport in remote areas reduced delivery times by over 50% compared to traditional ground transportation methods [25].

The reduction in delivery times directly impacts the speed of diagnosis and subsequent treatment. In emergency situations, such as delivering blood for transfusions or diagnostic samples for critical patient care, these time savings can have life-saving consequences. In Rwanda, where Zipline drones have been deployed to deliver medical supplies, there has been a 60% decrease in the time it takes to deliver blood products to remote health centers [25]. This has led to improved patient outcomes, particularly in maternal health emergencies where rapid access to blood transfusions is crucial.

Cost savings are another quantifiable benefit of drone-based transportation. A report by Otto and Williams (2020) found that drone deliveries in remote areas reduced per-delivery costs by approximately 50%, from $2.22 for ground vehicles to $0.88 for drones [27]. This significant cost reduction allows healthcare providers to allocate more resources to other areas of patient care, thereby improving the overall efficiency of healthcare delivery systems.

Moreover, the increased frequency of drone deliveries has improved the throughput of medical diagnostics. With drones able to make multiple trips in a day, healthcare facilities can process medical samples more rapidly, leading to faster diagnostic turnaround times and the earlier initiation of treatment. This has been observed in several regions where drones have enabled a 20–30% increase in the number of medical samples transported per day compared to traditional methods [26,27].

4.7. Quantitative Impact on Healthcare Delivery Outcomes

Drones have significantly improved healthcare delivery by reducing transportation times, increasing delivery frequency, and enhancing emergency response capabilities. In Rwanda, Zipline drones cut delivery times by 50–60%, while Matternet in Switzerland reduced transport times from over an hour to just seven minutes, leading to faster diagnoses and treatments [25,45]. Drones have also enabled a 20–30% increase in the number of medical samples transported per day [26], accelerating diagnostic processes.

In emergencies, drones ensure the rapid transport of critical supplies, improving patient outcomes, particularly in remote regions where timely intervention is vital [25,46]. Additionally, drone deliveries have reduced transportation costs by up to 50%, allowing healthcare systems to allocate more resources to patient care [27]. Overall, the use of drones has enhanced both the speed and efficiency of healthcare logistics, leading to better patient care and system-wide improvements.

5. Reliability and Security

The reliability and security of drone-based medical sample transportation are critical factors that have seen significant advancements in recent years. These improvements are largely driven by technological innovations in navigation, monitoring, and payload security systems, which together ensure the safe and secure transport of medical samples. These advancements have not only enhanced the reliability of drone operations but have also solidified their role in modern healthcare logistics [43,47–49].

5.1. Advanced Navigation Systems

Modern drones used in healthcare logistics are equipped with next-generation navigation systems that extend beyond traditional Global Positioning System (GPS) and inertial measurement units (IMUs). One of the most significant advancements in this area is the integration of AI-powered obstacle avoidance and object tracking, which allows drones to navigate complex environments with greater precision. The incorporation of the Unmanned Aerial Vehicle Benchmark: Object Detection and Tracking [50–52] has been pivotal in improving these capabilities, enabling drones to detect and track obstacles or moving objects in real time. This is especially crucial in urban environments where drones must maneuver around buildings, moving vehicles, and other obstacles to deliver medical samples swiftly and safely.

In addition to object detection, predictive analytics and machine learning models allow drones to anticipate potential obstacles or adverse weather conditions and make adjustments in real time. This not only reduces the risk of accidents but also ensures the timely and reliable delivery of critical medical supplies. By leveraging data from previous flights, these drones are capable of learning and adapting to new environments, making their operations more robust and dependable [25,52].

These advancements are particularly important in healthcare logistics, where reliability and precision are paramount. The ability to safely navigate congested or remote areas ensures that medical samples are transported without delays, maintaining their integrity throughout the journey [26].

5.2. Real-Time Monitoring and Communication

One of the most significant advancements in the field is the development of enhanced real-time monitoring and communication technologies. Drones are now equipped with multiple redundant communication channels, including 5G connectivity, which ensures continuous data transmission even in areas with traditionally weak signals. This improvement has led to more reliable drone operations, particularly in remote or rural regions where maintaining a strong communication link is challenging [44,53–55].

Additionally, real-time health monitoring systems have been introduced, allowing operators to track not only the drone's flight parameters but also the status of the medical payload [56,57]. These systems can monitor variables such as temperature, humidity, and vibration inside the payload compartment, ensuring that the medical samples remain within safe parameters throughout the journey. This level of monitoring is crucial for the transport of sensitive samples, such as blood or tissues, where even slight deviations from optimal conditions can compromise sample integrity [16].

5.3. Secure Payload Systems

The secure transportation of medical samples has seen considerable enhancements with the development of advanced payload management systems. Recent innovations include the integration of smart containers that are capable of real-time condition adjustments based on the payload's needs. For instance, these containers can autonomously regulate internal temperature and humidity levels to maintain the ideal environment for specific medical samples, such as vaccines or blood products [58,59].

Moreover, advancements in tamper-evident technology now allow for more sophisticated security measures. These systems include biometric or encrypted access controls that ensure only authorized personnel can handle or access the payload [60]. Additionally, the use of blockchain technology for tracking and documenting the chain of custody has been introduced, providing a transparent and immutable record of the sample's journey from collection to delivery [47]. This development is particularly important for maintaining legal and diagnostic integrity, especially in sensitive cases like forensic sample transportation [61].

5.4. Minimizing Risks of Contamination and Damage

The risk of contamination and damage to medical samples has been further minimized through the use of enhanced protective systems. Drones are now equipped with vibration dampening technology and shock-absorbent payload compartments that protect samples during flight, especially in turbulent conditions [62]. Additionally, the introduction of UV-C sterilization systems within the payload compartment offers an extra layer of protection, reducing the risk of microbial contamination during transport [63].

These advancements in contamination and damage prevention are crucial for maintaining the high standards required in medical logistics, particularly for samples that are highly sensitive or prone to degradation. By ensuring that samples are kept in optimal conditions throughout their journey, drones enhance the reliability of the healthcare supply chain and reduce the potential for compromised diagnostic results.

5.5. Vision-and-Language Navigation for UAVs

An emerging innovation in the field of UAV control is the use of Vision-and-Language Navigation (VLN), which allows drones to be guided through natural language instructions. This advancement is exemplified by AerialVLN: Vision-and-Language Navigation for UAVs [53,54], where UAVs are equipped with the ability to interpret linguistic commands alongside visual input to navigate complex environments autonomously. This integration of multi-modal data—both visual and linguistic—represents a significant shift in how UAVs can be operated in dynamic and unpredictable conditions.

In the context of medical logistics, VLN technology has the potential to revolutionize drone operations, especially in scenarios where pre-programmed flight paths or GPS data may be unavailable or insufficient. For example, in disaster-stricken areas or densely populated urban environments, VLN enables UAVs to follow real-time verbal instructions, making it easier for operators to adjust routes on the fly. This capability is critical when drones need to reach specific locations within a hospital complex or deliver medical samples in disaster zones where infrastructure is damaged and traditional navigation methods may fail.

The AerialVLN system works by combining computer vision algorithms with natural language processing (NLP) techniques, allowing UAVs to "understand" descriptive commands such as "fly to the large red building" or "navigate around the parked ambulance". The integration of visual data with language input provides a richer contextual understanding for the UAV, allowing it to make autonomous decisions even in environments with limited or no GPS signals. This offers a significant advantage over conventional UAV navigation systems, which rely solely on predefined waypoints or manual control [53].

Moreover, VLN can significantly reduce the technical complexity required for operating drones in medical logistics. Traditional UAV systems often necessitate specialized training for operators to manage flight paths and react to environmental obstacles. With VLN, healthcare workers or emergency responders with minimal drone experience can provide simple verbal commands to guide UAVs, thus broadening the accessibility of drone technology in healthcare settings. This could be particularly useful in remote or rural areas, where skilled UAV operators may not be readily available [53].

From an operational standpoint, integrating Vision-and-Language Navigation could improve the efficiency and responsiveness of medical drone deliveries. The adaptability of VLN allows UAVs to react to unforeseen circumstances, such as sudden changes in weather conditions or unexpected obstacles, making it more reliable for time-sensitive missions like transporting medical samples or emergency supplies. Furthermore, by enabling real-time communication between the drone and the operator, VLN could enhance coordination in emergency scenarios where immediate adjustments to the drone's flight path are necessary [53].

While VLN technology is still in its early stages, its potential to improve UAV functionality, particularly in healthcare logistics, is considerable. Future advancements in this area could further optimize the integration of natural language commands and visual data, increasing the accuracy and robustness of medical UAV operations. As these systems evolve, they are expected to become a vital component of next-generation drone fleets, enabling more efficient, adaptable, and user-friendly UAV operations in medical logistics.

6. Challenges and Future Directions

The implementation of drones in medical logistics, while promising, faces several barriers that must be addressed before widespread adoption can be realized. These challenges range from regulatory hurdles to technical limitations and scalability issues. The following sections explore some of the key barriers that healthcare providers and policymakers need to consider.

6.1. Regulatory and Legal Issues

The adoption of drone technology in the healthcare sector, particularly for the transportation of medical samples, is promising but faces significant regulatory and legal challenges [13,19]. These challenges stem from concerns about safety, privacy, airspace management, and the need for consistent and enforceable guidelines that ensure drones are used safely and effectively within the framework of existing healthcare regulations.

6.2. Airspace Management and Safety Concerns

One of the primary regulatory hurdles is the management of airspace, especially in urban areas where the risk of collisions with manned aircraft, buildings, and other obstacles is higher. Regulatory bodies like the Federal Aviation Administration (FAA) in the United States and the European Union Aviation Safety Agency (EASA) in Europe have established strict guidelines that govern how and where drones can operate. These regulations typically restrict drones from flying above certain altitudes, within certain proximities to airports, and over populated areas without special permissions [64–67].

For drones to be more widely adopted in healthcare, there is a need for regulatory frameworks that can accommodate the unique requirements of medical logistics. This includes creating designated air corridors for drones, similar to the concept of roads for ground vehicles, where drones can operate safely without interfering with manned aircraft. Additionally, there is a push for integrating unmanned traffic management (UTM) systems, which are designed to coordinate drone operations, avoid collisions, and manage airspace efficiently. The development and deployment of these systems are critical to ensuring that drones can be safely integrated into national airspace systems [27,67].

6.3. Privacy and Data Protection

Privacy concerns are another significant regulatory challenge [68]. The use of drones for medical sample transportation often involves the collection and transmission of sensitive data, including patient information and the status of medical samples. These data must be protected to comply with regulations such as the Health Insurance Portability and Accountability Act (HIPAA) in the United States and the General Data Protection Regulation (GDPR) in Europe [69]. These regulations impose strict requirements on how data are collected, stored, and transmitted to protect patient confidentiality [70].

To address these concerns, drones used in healthcare logistics must be equipped with secure communication channels and encryption protocols that ensure data privacy. Moreover, operators must implement robust cybersecurity measures to protect against data breaches and unauthorized access. Compliance with these regulations is not only a legal requirement but also critical to maintaining public trust in drone-based healthcare services [70].

6.4. Licensing and Certification Requirements

The operation of drones, particularly in commercial applications like healthcare, requires operators to be licensed and drones to be certified [48,71]. Regulatory bodies require drone operators to undergo training and obtain certifications that demonstrate their ability to safely operate drones in various conditions. This includes understanding airspace regulations, flight operations, and emergency procedures. Additionally, drones themselves must meet specific technical standards and be certified for safe operation, especially when carrying critical medical supplies [72].

The process of obtaining these licenses and certifications can be cumbersome and varies significantly between countries, creating a barrier to the widespread adoption of drones in healthcare. International harmonization of these licensing and certification processes would facilitate easier cross-border drone operations and contribute to the broader adoption of drones in global healthcare logistics [67].

6.5. Liability and Insurance Issues

Liability and insurance are also critical considerations in the regulatory landscape for drones. In the event of an accident or the loss of medical samples during transport, determining liability can be complex. Questions arise as to whether the drone operator, the healthcare provider, the drone manufacturer, or another party is responsible. This ambiguity makes it challenging to insure drone operations and can lead to costly legal disputes [27].

To mitigate these risks, there is a growing demand for clear liability frameworks that define the responsibilities of all parties involved in drone operations. Additionally, specialized insurance products are being developed to cover the unique risks associated with drone-based logistics, including coverage for payload loss, operational disruptions, and third-party damages [67].

6.6. Future Directions in Regulatory Frameworks

To overcome these regulatory and legal challenges, governments and international regulatory bodies are working on developing more comprehensive and flexible frameworks that can accommodate the rapid advancements in drone technology. For example, the FAA's recent implementation of Part 107 regulations in the U.S. provides a set of rules for small unmanned aircraft systems (UAS), including provisions for waivers that allow for more complex operations such as beyond visual line of sight (BVLOS) flights, night operations, and flights over people [73–75].

In Europe, the EASA has introduced regulations that categorize drone operations based on risk, with specific requirements for "open", "specific", and "certified" categories. These regulations aim to balance safety with operational flexibility, enabling more widespread use of drones in healthcare while maintaining stringent safety standards [72,76,77] (Table 3).

Table 3. Challenges and Future Directions in Drone-Based Medical Sample Transportation.

Challenge	Description	Future Direction
Regulatory and Legal Issues	Complex regulations, airspace management, and legal liability concerns hinder widespread adoption.	Develop comprehensive, flexible regulatory frameworks; international collaboration for standardization.
Technical Limitations	Limited battery life, vulnerability to weather conditions, and reliance on communication networks.	Advances in battery technology, AI for navigation, and IoT for seamless communication.
Ethical and Privacy Concerns	Handling and securing sensitive medical data during drone transportation.	Implementation of robust encryption protocols, compliance with data protection regulations (HIPAA, GDPR).
Integration with Healthcare Systems	Ensuring compatibility and interoperability with existing healthcare infrastructure.	Development of standardized protocols, integration with HIS, LIMS, EHRs, and automated sample handling.

7. Accessibility

Drones have demonstrated significant potential in enhancing the accessibility of medical sample transportation, particularly in regions where traditional transportation methods are hindered by geographic, infrastructural, or logistical challenges [5,6,78–80]. By leveraging their ability to fly directly over obstacles, drones can bridge the gap between healthcare facilities and remote or underserved communities, ensuring that critical medical samples are transported efficiently and reliably.

7.1. Overcoming Geographic Barriers

In many parts of the world, geographic barriers such as mountains, rivers, and dense forests can impede the timely transportation of medical samples. Drones can bypass these obstacles by flying directly to their destinations, significantly reducing travel time and ensuring that samples reach laboratories or hospitals in a timely manner. For instance, in countries with rugged terrains like Nepal, drones have been used to deliver medical supplies and samples across mountainous regions, where ground transportation is often slow and unreliable [81,82].

7.2. Serving Remote and Underserved Areas

Remote and underserved areas often lack adequate healthcare infrastructure, making it difficult to transport medical samples quickly and efficiently. Drones provide a vital link between these areas and central healthcare facilities, enabling the rapid transportation of diagnostic samples, vaccines, and medications. For example, in rural parts of Africa, drones operated by companies like Zipline have been used to deliver blood products and medical samples to remote clinics, drastically reducing delivery times and improving patient outcomes [25,83].

7.3. Disaster Response and Emergency Situations

In the aftermath of natural disasters or during emergency situations, traditional transportation networks can be disrupted, making it challenging to deliver medical samples and supplies. Drones offer a flexible and resilient solution, capable of accessing affected areas quickly and efficiently. During the 2017 hurricanes in Puerto Rico, drones were deployed to deliver medical supplies and samples to areas cut off by flooding and infrastructure damage. This rapid response capability is crucial for maintaining healthcare services during crises [84–87].

7.4. Facilitating Regular Medical Services in Remote Areas

Drones also facilitate regular medical services by enabling frequent and reliable transportation of medical samples, vaccines, and medications. In many remote areas, regular supply chains are inconsistent, and healthcare facilities often face shortages of essential supplies. Drones can establish a regular and reliable supply chain, ensuring that remote healthcare facilities are well-stocked and that medical samples are transported promptly for diagnostic testing [26,88].

8. Integration with Healthcare Systems

The integration of drones into healthcare systems represents a significant advancement in the transportation of medical samples, promising to enhance the efficiency, accuracy, and speed of healthcare delivery [18,89]. However, to realize this potential it is necessary to overcome several challenges related to the interoperability of drone systems with existing healthcare infrastructure, the automation of sample handling and processing, and the standardization of protocols across different healthcare facilities.

8.1. Interoperability with Existing Healthcare Infrastructure

Interoperability is a critical factor in the successful integration of drones into healthcare systems. Drones must be able to seamlessly interact with existing healthcare infrastructure, such as hospital information systems (HIS), laboratory information management systems (LIMS), and electronic health records (EHRs). This integration is essential for ensuring that data related to medical samples—such as tracking information, temperature logs, and chain-of-custody documentation—can be accurately and efficiently transferred across systems [90].

One of the key benefits of interoperability is the ability to maintain real-time communication between drones and healthcare facilities. For instance, drones equipped with sensors can monitor and transmit real-time data about the condition of the samples they are carrying, such as temperature and humidity levels. These data can be automatically logged into the LIMS, ensuring that healthcare providers can monitor the integrity of the samples throughout the transportation process. If a drone detects that a sample is at risk of being compromised (e.g., due to a rise in temperature), it can send an immediate alert to the relevant healthcare providers, allowing them to take corrective action. This real-time data integration is crucial for maintaining the quality of medical samples and ensuring accurate diagnostic outcomes [27,61,90].

Moreover, interoperability with EHRs enables the automatic updating of patient records with information about the sample transportation process, such as the time of collection, transport duration, and arrival at the laboratory. This integration ensures that healthcare providers have a complete and up-to-date view of the patient's diagnostic timeline, allowing for more informed decision-making and faster treatment initiation [90,91].

8.2. Automated Sample Handling and Processing

The integration of drones into healthcare systems also involves the automation of sample handling and processing. Automated systems for receiving and processing samples delivered by drones can significantly enhance the efficiency of laboratory operations [13,14,92]. For example, upon arrival at a healthcare facility, drones could interface with automated reception systems that scan and log the samples into the LIMS, verify their integrity, and direct them to the appropriate diagnostic instruments. This process reduces the need for manual handling, minimizing the risk of errors and contamination, and speeds up the time from sample arrival to diagnostic processing.

Automated sample processing systems can also be programmed to prioritize certain samples based on predefined criteria, such as those marked as urgent or critical. This prioritization ensures that time-sensitive diagnostics are performed as quickly as possible, further improving patient outcomes. Additionally, these systems can be integrated with predictive analytics tools that use historical data to optimize sample routing and processing workflows, thereby maximizing the efficiency of healthcare operations [93,94].

8.3. Standardization and Protocol Development

A major challenge in the integration of drones into healthcare systems is the standardization of protocols and procedures across different facilities [13,15]. Standardized protocols are essential for ensuring consistency and reliability in drone operations, particularly when multiple healthcare providers and facilities are involved. These protocols should cover all aspects of drone usage, including flight operations, sample handling, data management, and compliance with regulatory requirements.

For instance, standardized flight protocols would ensure that drones operate within designated air corridors, follow consistent procedures for takeoff and landing, and adhere to specific safety guidelines. Similarly, standardized handling protocols would dictate how samples should be packaged, labeled, and stored during transit to maintain their integrity. These protocols would also include guidelines for the secure transmission of data between drones and healthcare systems, ensuring that sensitive patient information is protected throughout the transportation process [6,67].

The development of these standards would require collaboration between healthcare providers, drone manufacturers, regulatory bodies, and industry organizations. International organizations, such as the International Organization for Standardization (ISO), could play a key role in developing and disseminating these standards, ensuring that drone operations are consistent and reliable across different regions and healthcare systems.

8.4. Integration with Emerging Technologies

The future integration of drones into healthcare systems will likely involve leveraging emerging technologies such as artificial intelligence (AI) and the Internet of Things (IoT). AI can be used to enhance the decision-making capabilities of drones, allowing them to optimize flight paths, predict and avoid potential hazards, and adapt to changing environmental conditions in real-time. Meanwhile, IoT can facilitate the seamless connectivity of drones with other devices and systems within the healthcare ecosystem, enabling the real-time exchange of data and the automation of complex workflows [49,95–97].

For example, IoT-enabled sensors on drones can continuously monitor environmental conditions, such as temperature and humidity, and automatically adjust the drone's internal climate control systems to maintain optimal conditions for the samples [98]. AI algorithms can analyze flight data to improve route efficiency, reducing energy consumption and extending battery life. These advancements will further enhance the integration of drones into healthcare systems, making them an even more valuable tool for medical logistics [99].

9. Case Studies

The case studies in this review were carefully selected to showcase a variety of applications of drone technology in different healthcare logistics settings, with attention paid to both geographical and operational diversity. Each case study was chosen based on its ability to highlight specific logistical challenges and the corresponding solutions provided by drone technology. The selection criteria focused on three main aspects: the operational environment (urban vs. rural); the type of medical supplies being transported; and the specific challenges being addressed, such as traffic congestion, geographical barriers, or emergency healthcare needs.

1. Zipline in Rwanda:

Zipline's operation in Rwanda was chosen due to its pioneering role in using drones to deliver critical medical supplies, such as blood, to remote and underserved areas. This case illustrates how drones can overcome the significant geographical barriers in rural regions where road infrastructure is lacking. Rwanda's challenging terrain and healthcare access disparities make this a compelling case for demonstrating the potential of drone logistics in improving healthcare delivery. Zipline's success in reducing delivery times from hours to minutes has had a profound impact on healthcare outcomes, especially in emergency situations [25,100–113].

2. Matternet in Switzerland:

The Matternet project in Zurich, Switzerland, was selected to represent drone operations in an urban setting, where traffic congestion can significantly delay the transportation of medical supplies. This case study demonstrates how drones can offer a sustainable solution to logistical delays in densely populated areas. The operation between hospitals in Zurich reduced transportation times from hours by road to just seven minutes by drone [101,103]. Matternet's work showcases the environmental and operational benefits of drone logistics in reducing carbon emissions while improving healthcare efficiency in urban environments [104].

3. Swoop Aero in Africa and the Pacific Islands:

Swoop Aero's operations in Africa and the Pacific Islands were selected to highlight how drones can improve healthcare access in geographically isolated areas. The case of Malawi, where Swoop Aero delivered over 500,000 vaccines and medical supplies to remote communities, demonstrates the critical role drones can play in improving vaccination rates and overall health outcomes in areas with limited road infrastructure [50,51,112,113]. This case study was chosen to emphasize the scalability and sustainability of drone networks in challenging environments [112,113].

4. Wingcopter in Vanuatu and Tanzania:

Wingcopter was chosen for its role in delivering essential medical supplies, such as vaccines and medications, to remote islands and rural areas in Vanuatu and Tanzania. This case highlights the ability of drones to operate in extreme conditions, providing timely healthcare services where traditional methods would take significantly longer or be impossible due to geographic isolation. The choice of Wingcopter illustrates the critical importance of drone technology in overcoming logistical barriers in healthcare delivery for hard-to-reach populations [112–116].

5. Rationale for Case Selection:

Each of these case studies was selected based on their unique contributions to healthcare logistics and the diverse environments they represent. The aim was to provide a comprehensive understanding of how drone technology can address different types of logistical challenges, from urban traffic congestion to remote access issues. By examining these cases, the review aims to offer practical insights into how drones can be implemented in various healthcare settings, highlighting both the successes and ongoing challenges, such as regulatory hurdles and operational scalability [25,104,108].

9.1. Matternet

Matternet has established itself as a leader in the field of drone delivery for healthcare, particularly through its partnership with UPS. In one of their most notable projects, Matternet drones are used to transport diagnostic samples between hospitals in Zurich, Switzerland. The route covers five kilometers (about 3.1 miles) and is recognized as the world's longest urban drone delivery route. The use of drones has reduced the transportation time for medical samples from hours to just seven minutes, demonstrating a significant improvement in the efficiency of healthcare logistics. This project also highlights the potential of drones to alleviate traffic congestion in urban areas and reduce carbon emissions, making it a sustainable solution for urban healthcare delivery [101–103].

In the United States, Matternet has also partnered with WakeMed Health & Hospitals in Raleigh, North Carolina [104]. This partnership, which began in 2019, marked the first FAA-approved commercial drone delivery service for medical samples in the U.S. Drones are used to transport samples across the WakeMed campus, which has reduced the time required for sample delivery from over an hour by car to just a few minutes by drone. This service has not only improved the speed and efficiency of medical testing but has also allowed healthcare professionals to focus more on patient care, as the logistics of sample transportation are handled autonomously [105].

9.2. Zipline

Zipline is another pioneer in the use of drones for healthcare logistics, particularly in remote and underserved regions [106]. Since its launch in Rwanda in 2016, Zipline has expanded its operations to several other countries, including Ghana, Nigeria, and the United States. In Rwanda, Zipline's drones have completed over 200,000 deliveries, flying more than 2 million kilometers (about 1.2 million miles) to deliver blood, vaccines, and essential medications to remote clinics. This service has drastically reduced the delivery time for critical supplies, which previously could take hours or even days by road, to just 30 min by drone. The impact of this service has been profound, particularly in emergency situations where the timely delivery of blood has saved countless lives [107,108].

In the United States, Zipline has partnered with healthcare providers to integrate drone delivery into their logistics networks. For instance, in North Carolina, Zipline drones are used to deliver medical supplies to hospitals within the state, further enhancing the efficiency of healthcare delivery. The company's drones are capable of carrying up to 1.75 kg (3.85 pounds) of cargo over a distance of 160 km (100 miles) on a single battery charge, making them highly efficient for long-distance deliveries in both urban and rural settings [109,110].

9.3. Jedsy

Jedsy, a relatively new entrant in the drone delivery market, has introduced an innovative approach to medical logistics. Unlike traditional drones that require a designated landing area, Jedsy drones are designed to attach directly to the windows of healthcare facilities, allowing for the seamless and secure transfer of medical goods. This unique feature not only speeds up the delivery process but also minimizes the risk of contamination. Jedsy has been operational in Switzerland, where it is used to deliver medical samples and supplies to hospitals in both urban and rural areas. The company's drones can make deliveries regardless of weather conditions, which ensures that critical medical supplies are delivered on time, even in challenging environments [108,111].

9.4. Swoop Aero in Africa and the Pacific Islands

Swoop Aero, an Australian drone logistics company, has been instrumental in improving healthcare delivery in remote areas of Africa and the Pacific Islands. In Malawi, Swoop Aero drones have delivered over 500,000 vaccines and medical supplies to remote communities, dramatically improving healthcare access in these regions. The drones can carry up to three kilograms (about 6.6 pounds) of cargo over distances of up to 130 km (81 miles) per flight. This capability has been particularly valuable in increasing vaccination rates and improving health outcomes in areas where traditional transportation methods are slow and unreliable. Swoop Aero's success in these regions highlights the critical role of drones in overcoming logistical barriers in global health [112,113].

9.5. Wingcopter in Vanuatu and Tanzania

Wingcopter has made significant contributions to healthcare logistics in remote areas of Vanuatu and Tanzania. In Vanuatu, Wingcopter drones have been used to deliver vaccines to remote islands, reducing delivery times from hours or even days to just minutes. This service has been crucial in ensuring that vaccines are delivered safely and promptly to children in hard-to-reach areas. In Tanzania, Wingcopter drones have partnered with local health organizations to deliver blood, medications, and other critical supplies to remote health centers. The drones can carry up to six kilograms (about 13 pounds) of medical supplies and travel up to 100 km (about 62 miles) on a single charge, making them a highly effective solution for healthcare delivery in challenging environments [114–116].

9.6. Comparative Analysis of Case Studies: Identifying Common Themes

The various case studies presented in this review, including Zipline in Rwanda, Matternet in Switzerland, Swoop Aero in Africa, and Wingcopter in Vanuatu and Tanzania, demonstrate consistent themes in the benefits and challenges of drone-based medical logistics.

1. Speed and Efficiency

Across all the case studies, a significant common benefit is the dramatic reduction in transportation times for medical supplies and samples. For example, Zipline drones reduced delivery times by up to 60% in rural Rwanda, while Matternet achieved a reduction from hours to just 7 min in urban Switzerland [25,101]. This improvement in speed directly impacts patient outcomes, particularly in emergency scenarios.

2. Accessibility to Remote and Underserved Areas

Another shared theme is the enhanced accessibility that drones provide to remote or underserved regions. Swoop Aero in Malawi and Wingcopter in Vanuatu have demonstrated the ability to reach geographically isolated areas, ensuring the timely delivery of vaccines and medical supplies. This is especially important in regions where road infrastructure is underdeveloped or during emergencies where traditional transport routes are compromised [113,114].

3. Cost-Effectiveness

Cost reductions are also a consistent theme across the case studies. For example, Zipline and Swoop Aero operations in remote regions reduced transportation costs by approximately 50%, making medical logistics more affordable for healthcare providers [25,27]. This is particularly beneficial in low-income regions where healthcare budgets are constrained.

4. Technological Challenges and Solutions

Each case study highlights the role of advanced technology, such as AI-powered navigation, real-time monitoring, and secure payload systems, in overcoming logistical barriers. However, they also point out common technological challenges, including limited flight range, battery life, and weather conditions. The integration of technologies like AI, blockchain, and autonomous navigation systems has emerged as a solution to many of these challenges, ensuring that medical drones maintain reliability and security during flights [47,53].

5. Regulatory and Legal Challenges

Despite the benefits, each case study also underscores the regulatory and legal hurdles that need to be addressed for wider adoption. Issues related to airspace management, data privacy, and operational certifications remain a challenge, particularly in urban areas or across international borders. The development of robust regulatory frameworks, such as those in the Matternet case study, is critical to the future scalability of drone-based medical logistics [104].

6. Sustainability and Scalability

A key theme across the case studies is the potential for scalability. As demonstrated by Zipline and Swoop Aero, drone networks can be expanded to cover larger regions and handle more deliveries. However, scalability depends heavily on continued technological advancements, regulatory approval, and investment in infrastructure. Moreover, ensuring that drone systems are sustainable in the long term—particularly in terms of energy consumption and environmental impact—remains a common concern across all case studies [108,114].

10. Conclusions

The integration of drone technology into the transportation of medical samples marks a significant advancement in healthcare logistics, offering the potential to transform the way in which medical supplies and specimens are delivered. This review has explored the technological advancements, practical applications, and challenges associated with the use of drones in this critical area of healthcare. By summarizing the potential impact and considering future directions, we can better understand how drones are poised to revolutionize medical sample transportation.

10.1. Summary of Key Benefits

Drones provide numerous benefits in the transportation of medical samples, particularly in terms of speed and efficiency. In urban areas, where traffic congestion can significantly delay ground-based transportation, drones offer a rapid and direct method of delivery that can drastically reduce transportation times. This speed is especially crucial for time-sensitive medical diagnostics and treatments, where delays could compromise patient outcomes. In remote or underserved regions, drones overcome geographic and infrastructural barriers that hinder traditional transportation methods. Their ability to reach areas that are otherwise inaccessible makes them invaluable during emergencies and natural disasters, where swift access to medical supplies can be a matter of life and death.

Cost-effectiveness is another key advantage of using drones in medical logistics. By reducing reliance on ground vehicles and human couriers, drones lower transportation costs. The increased frequency of deliveries that drones enable can also lead to cost savings across the healthcare process. Faster diagnostic turnaround times and more timely treatments, facilitated by the rapid transport of samples, reduce the overall burden on healthcare systems and improve patient care.

Moreover, drones enhance the reliability and security of medical sample transportation. Equipped with advanced navigation systems, real-time monitoring capabilities, and secure payload mechanisms, drones ensure that medical samples are transported safely, with a reduced risk of contamination, loss, or damage. This reliability strengthens the overall healthcare supply chain, making it more resilient and dependable.

10.2. Addressing Challenges

Despite these benefits, several challenges must be addressed to fully realize the potential of drones in medical sample transportation. Regulatory and legal issues remain a significant barrier to widespread adoption. The establishment of clear guidelines and regulations for the safe and compliant use of drones in healthcare is essential for their broader implementation. Additionally, technical limitations such as limited battery life, vulnerability to adverse weather conditions, and the need for reliable communication networks must be overcome. Ongoing research and development efforts are focused on addressing these limitations through the improvement of materials, the introduction of redundant systems, and the advancement of collision-avoidance technologies.

Ethical and privacy concerns also arise with the use of drones, particularly regarding the handling and transportation of sensitive medical data. Ensuring that drone operations adhere to ethical standards and protect patient privacy is crucial for maintaining public trust. Furthermore, the successful integration of drone technology into existing healthcare systems requires collaboration between technology developers, healthcare providers, and regulatory bodies. Developing standardized protocols and interoperable systems will be key to realizing the full potential of drones in medical sample transportation.

11. Discussion

This review has provided a comprehensive analysis of the current advancements in drone-based medical logistics, emphasizing case studies that showcase the potential benefits and challenges of drones in healthcare. Through an examination of technological innovations, such as AI-driven navigation systems, real-time monitoring, and secure payload management, the review has demonstrated how drones can significantly reduce transportation times and improve healthcare accessibility in underserved regions. However, it is essential to critically analyze these findings in the context of the broader healthcare logistics landscape.

11.1. Comparison of Findings

The case studies reviewed—particularly those in Rwanda and Ghana—illustrate how drones can overcome geographical barriers and reduce the time needed to transport critical medical supplies. These studies align with findings from other regions, such as Switzerland and the United States, where drones have been successfully deployed in urban environments, reducing delivery times and operational costs [7,10]. While these examples demonstrate the immediate benefits of drone-based logistics, the broader literature also highlights several challenges, particularly around regulatory limitations, privacy concerns, and operational scalability [14,15,45,46].

One of the key themes that emerged from the reviewed literature is the difficulty in integrating drone systems into existing healthcare infrastructure. While case studies provide evidence of drones improving transportation efficiency, many healthcare facilities still rely heavily on traditional logistics methods, and there is a gap in understanding how drones can be integrated seamlessly with existing hospital information systems (HIS) and supply chain technologies. This presents an opportunity for future research to explore frameworks for better integration, particularly as drone technology becomes more advanced.

11.2. Key Challenges

Several challenges remain, despite the demonstrated potential of drones in healthcare logistics. Regulatory issues are one of the primary barriers to widespread adoption. Current regulations in many countries limit the use of drones for healthcare purposes, particularly in densely populated areas or over long distances where beyond visual line of sight (BVLOS) flights are not yet fully authorized. Furthermore, the use of drones raises privacy and data security concerns, particularly when transporting sensitive medical samples that could be compromised if drones are tampered with or if flight data are intercepted [15].

Another critical challenge is scalability. While case studies in specific regions show the effectiveness of drones on a smaller scale, there is still limited evidence regarding the long-term sustainability and scalability of these systems. Can drones consistently handle large volumes of medical deliveries across diverse geographical regions? A recent study assessing the carbon dioxide (CO_2) footprint of medical sample transportation found that drones offer a significantly greener alternative to combustion vehicles, with lower CO_2 emissions compared to both combustion and electric cars [115]. However, scaling this green approach to large healthcare systems will require further research on how drones can sustainably manage high transportation volumes.

Furthermore, the preanalytic integrity of blood samples transported via drones has been a subject of interest, with recent studies showing that blood samples transported by drones retain their integrity when compared to traditional transport methods [116]. Ensuring that drones can reliably maintain the quality of medical samples during long flights and under varying environmental conditions is another challenge that must be addressed for widespread adoption.

11.3. Implications for Medical Logistics

The findings of this review have significant implications for the field of medical logistics. Drones have the potential to transform healthcare delivery by reducing transportation times and improving access to medical services, particularly in underserved regions. However, for this transformation to be realized, healthcare providers, policymakers, and logistics companies must work together to overcome the challenges identified in this review. The regulatory landscape will need to evolve to accommodate drones as a routine part of healthcare delivery, and investments must be made in infrastructure and training to ensure that drone operations are safe, efficient, and scalable.

Moreover, the integration of drones with existing technologies—such as autonomous vehicles and supply chain management systems—will be essential to maximizing their potential. As technological advancements continue to evolve, the collaboration between healthcare institutions, government bodies, and tech innovators will determine the future success of drones in medical logistics.

12. Future Directions

As drone technology continues to evolve, the future of medical sample transportation will be defined by several key technological milestones, challenges, and sustainability goals. One of the most critical developments will be the improvement of battery technology, which currently limits the flight time and range of drones. Extending battery life is essential for enabling drone operations to cover larger geographic areas, particularly in rural and remote regions where long-distance flights are required. In parallel, advancements in charging infrastructure and battery efficiency will be necessary to support sustained and scalable drone networks. These improvements will not only enhance operational capability but also reduce costs and ensure that drone systems can be deployed consistently in diverse environments.

Another significant milestone will be the integration of autonomous navigation systems powered by artificial intelligence (AI). These systems will enable drones to navigate increasingly complex environments, such as dense urban areas or unpredictable rural terrains, with minimal human intervention. This technology will enhance reliability by allowing drones to operate safely in both urban and rural settings while adhering to dynamic airspace regulations. Furthermore, AI-driven systems can optimize flight paths in real time, accounting for factors such as weather, air traffic, and infrastructure obstacles, thereby improving the overall efficiency of medical sample transportation. One crucial element in this advancement is the implementation of beyond visual line of sight (BVLOS) flights, which are currently limited by regulatory frameworks. BVLOS will allow drones to travel longer distances autonomously, vastly expanding their operational range, particularly for remote healthcare facilities.

In addition to advancements in technology, regulatory developments will play a pivotal role in the long-term success of drone-based medical transportation. Governments and aviation authorities must develop flexible and comprehensive frameworks that accommodate the growing use of drones in shared airspace, particularly in densely populated urban areas. A key part of this will be the creation of unmanned traffic management (UTM) systems, which will be critical to ensuring the safe and efficient coordination of multiple drones operating simultaneously. Such systems will enable real-time communication between drones and ground-based control centers, minimizing the risk of collisions and optimizing the efficiency of airspace usage. Additionally, regulatory frameworks must evolve to address issues related to privacy, data security, and operational accountability, particularly in healthcare, where patient information and sample integrity are of paramount concern.

As drone networks expand, ensuring their sustainability is essential for long-term scalability. One of the most effective ways to minimize the environmental impact of drone operations is through the development of electric-powered drones, which produce significantly lower carbon emissions compared to traditional fuel-powered vehicles. As battery technology advances, drones will become even more energy-efficient, further extending their range while reducing their environmental footprint. AI-driven route optimization will also contribute to environmental sustainability by minimizing energy consumption through efficient path planning and reducing unnecessary flights. Moreover, adopting recyclable materials in drone manufacturing and establishing battery recycling programs will reduce the environmental impact associated with drone production and disposal. This approach to sustainability will ensure that drone operations not only provide logistical benefits but also contribute to reducing the overall carbon footprint of healthcare transportation.

The scalability of drone-based transportation systems will depend on the continued integration of drones with existing healthcare logistics networks. Hospital information systems (HIS) and supply chain management technologies will need to be seamlessly integrated with drone networks to create an automated, real-time healthcare delivery infrastructure. Drones, along with other emerging technologies such as autonomous ground vehicles and robotic delivery systems, will form a multi-modal logistics network, with drones handling long-distance aerial deliveries and autonomous vehicles or robots completing the "last mile" of the delivery. This integration will significantly enhance efficiency, particularly in urban areas or complex healthcare facilities, where human intervention can be minimized.

The combined use of autonomous vehicles, robots, and drones represents the next frontier of medical logistics, enabling a system where drones handle high-speed, long-distance transportation, and robots manage localized distribution. Autonomous ground vehicles can complement drone deliveries by transporting medical samples or supplies from the drone landing site to specific departments or clinics within a hospital, ensuring that the entire supply chain operates seamlessly. For instance, while a drone can swiftly transport blood samples to a hospital, a robotic system can complete the delivery to the laboratory for immediate testing, reducing human handling and enhancing speed. Additionally, AI systems could oversee the coordination of these various autonomous technologies, ensuring that tasks are dynamically allocated based on real-time factors like traffic, weather, or facility availability.

Sustainability and scalability efforts can also be supported through regulatory incentives and frameworks that promote the use of low-emission, eco-friendly drones in healthcare logistics. Governments and healthcare organizations could adopt policies that encourage investment in green technologies, fostering an industry-wide shift towards more sustainable practices.

The long-term technological roadmap for drone-based medical transportation is promising but requires sustained innovation in several areas, including battery technology, AI-driven automation, autonomous navigation, and regulatory adaptation. Coupled with a strong focus on sustainability and integration with emerging technologies, these advancements will enable drones to become a central component of healthcare logistics. By improving access, efficiency, and patient outcomes on a global scale, drone systems will revolutionize healthcare delivery while maintaining a minimal environmental impact. The integration of multi-modal technologies, such as autonomous ground vehicles and robotic systems, will further enhance the flexibility and effectiveness of medical sample transportation networks, positioning drones as a cornerstone of the future healthcare infrastructure.

13. Limitations

While this review provides a comprehensive analysis of the current advancements in drone-based medical sample transportation, it is important to acknowledge several limitations. First, much of the data presented are drawn from case studies conducted in specific regions, such as Rwanda, Ghana, and Switzerland, which may not be fully generalizable to other healthcare systems or geographical locations with differing infrastructure and regulatory environments. The regulatory and technological landscapes vary significantly between countries, and therefore, the findings related to drone scalability and operational efficiency may not apply universally.

Additionally, the reviewed studies focus on short-term implementation and outcomes, which limits the ability to assess the long-term sustainability and scalability of drone operations in healthcare logistics. Further research is needed to explore how drones can be integrated into large-scale healthcare systems and the challenges that may arise over time, particularly concerning battery technology, cost efficiency, and regulatory frameworks.

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References

1. Wilson, M.L. General principles of specimen collection and transport. *Clin. Infect. Dis.* **1996**, *22*, 766–777. [CrossRef] [PubMed]
2. Verma, S.; Malik, Y.S.; Singh, G.; Dhar, P.; Singla, A.K. Aseptic Collection, Preservation, and Dispatch of Samples for Disease Diagnosis. In *Core Competencies of a Veterinary Graduate*; Springer Nature: Singapore, 2024; pp. 101–117.
3. Makitalo, O.; Liikanen, E. Improving quality at the preanalytical phase of blood sampling: Literature review. *Int. J. Biomed. Lab. Sci.* **2013**, *2*, 7–16.
4. Plebani, M. Pre-analytical errors and patient safety/Preanaliticke greske i bezbednost pacijenata. *J. Med. Biochem.* **2012**, *31*, 265. [CrossRef]
5. Watson, S.I.; Sahota, H.; Taylor, C.A.; Chen, Y.-F.; Lilford, R.J. Cost-effectiveness of health care service delivery interventions in low and middle income countries: A systematic review. *Glob. Health Res. Policy* **2018**, *3*, 1–14. [CrossRef]
6. Sewell, J.L.; Velayos, F.S. Systematic review: The role of race and socioeconomic factors on IBD healthcare delivery and effectiveness. *Inflamm. Bowel Dis.* **2012**. [CrossRef] [PubMed]
7. Bagloee, S.A.; Tavana, M.; Asadi, M.; Oliver, T. Autonomous vehicles: Challenges, opportunities, and future implications for transportation policies. *J. Mod. Transp.* **2016**, *24*, 284–303. [CrossRef]
8. Liu, Z.; Zhang, Y.; Yu, X.; Yuan, C. Unmanned surface vehicles: An overview of developments and challenges. *Annu. Rev. Control* **2016**, *41*, 71–93. [CrossRef]
9. Wercholuk, A.N.; Parikh, A.A.; Snyder, R.A. The road less traveled: Transportation barriers to cancer care delivery in the rural patient population. *JCO Oncol. Pract.* **2022**, *18*, 652–662. [CrossRef]
10. Labib, N.S.; Brust, M.R.; Danoy, G.; Bouvry, P. The rise of drones in internet of things: A survey on the evolution, prospects and challenges of unmanned aerial vehicles. *IEEE Access* **2021**, *9*, 115466–115487. [CrossRef]
11. Azmat, M.; Kummer, S. Potential applications of unmanned ground and aerial vehicles to mitigate challenges of transport and logistics-related critical success factors in the humanitarian supply chain. *Asian J. Sustain. Soc. Responsib.* **2020**, *5*, 3. [CrossRef]
12. Mohsan, S.A.H.; Khan, M.A.; Noor, F.; Ullah, I.; Alsharif, M.H. Towards the unmanned aerial vehicles (UAVs): A comprehensive review. *Drones* **2022**, *6*, 147. [CrossRef]
13. De Silvestri, S.; Capasso, P.J.; Gargiulo, A.; Molinari, S.; Sanna, A. Challenges for the Routine Application of Drones in Healthcare: A Scoping Review. *Drones* **2023**, *7*, 685. [CrossRef]

14. Marmaglio, P.; Consolati, D.; Amici, C.; Tiboni, M. Autonomous Vehicles for Healthcare Applications: A Review on Mobile Robotic Systems and Drones in Hospital and Clinical Environments. *Electronics* **2023**, *12*, 4791. [CrossRef]
15. Emimi, M.; Khaleel, M.; Alkrash, A. The current opportunities and challenges in drone technology. *Int. J. Electr. Eng. Sustain.* **2023**, *1*, 74–89.
16. Patel, K.; El-Khoury, J.M.; Simundic, A.-M.; Farnsworth, C.W.; Broell, F.; Genzen, J.R.; Amukele, T.K. Evolution of blood sample transportation and monitoring technologies. *Clin. Chem.* **2021**, *67*, 812–819. [CrossRef]
17. Amukele, T.K.; Hernandez, J.; Snozek, C.L.; Wyatt, R.G.; Douglas, M.; Amini, R.; Street, J. Drone transport of chemistry and hematology samples over long distances. *Am. J. Clin. Pathol.* **2017**, *148*, 427–435. [CrossRef]
18. Scott, J.; Scott, C. Drone delivery models for healthcare. In Proceedings of the 50th Hawaii International Conference on System Sciences, Waikoloa, HI, USA, 4–7 January 2017; pp. 1–8.
19. Euchi, J. Do drones have a realistic place in a pandemic fight for delivering medical supplies in healthcare systems problems? *Chin. J. Aeronaut.* **2021**, *34*, 182–190. [CrossRef]
20. Nisingizwe, M.P.; Ndishimye, P.; Swaibu, K.; Nshimiyimana, L.; Karame, P.; Dushimiyimana, V.; Musabyimana, J.P.; Musanabaganwa, C.; Nsanzimana, S.; Law, M.R. Effect of unmanned aerial vehicle (drone) delivery on blood product delivery time and wastage in Rwanda: A retrospective, cross-sectional study and time series analysis. *Lancet Glob. Health* **2022**, *10*, e564–e569. [CrossRef]
21. Hii, M.S.Y.; Courtney, P.; Royall, P.G. An evaluation of the delivery of medicines using drones. *Drones* **2019**, *3*, 52. [CrossRef]
22. Ling, G.; Draghic, N. Aerial drones for blood delivery. *Transfusion* **2019**, *59*, 1608–1611. [CrossRef]
23. Johnson, A.M.; Cunningham, C.J.; Arnold, E.; Rosamond, W.D.; Zègre-Hemsey, J.K. Impact of using drones in emergency medicine: What does the future hold? *Open Access Emerg. Med.* **2021**, *13*, 487–498. [CrossRef] [PubMed]
24. Nyaaba, A.A.; Ayamga, M. Intricacies of medical drones in healthcare delivery: Implications for Africa. *Technol. Soc.* **2021**, *66*, 101624. [CrossRef]
25. Haidari, L.A.; Brown, S.T.; Ferguson, M.; Bancroft, E.; Spiker, M.; Wilcox, A.; Ambikapathi, R.; Sampath, V.; Connor, D.L.; Lee, B.Y. The economic and operational value of using drones to transport vaccines. *Vaccine* **2016**, *34*, 4062–4067. [CrossRef] [PubMed]
26. Otto, P.; Williams, J. Cost-effectiveness of drone use for medical sample transport: A comparative analysis. *Health Syst.* **2020**, *9*, 102–112.
27. Kellermann, R.; Biehle, T.; Fischer, L. Drones for parcel and passenger transportation: A literature review. *Transp. Res. Interdiscip. Perspect.* **2020**, *4*, 100088. [CrossRef]
28. Johannessen, K.A. A conceptual approach to time savings and cost competitiveness assessments for drone transport of biologic samples with unmanned aerial systems (Drones). *Drones* **2022**, *6*, 62. [CrossRef]
29. Robakowska, M.; Ślęzak, D.; Żuratyński, P.; Tyrańska-Fobke, A.; Robakowski, P.; Prędkiewicz, P.; Zorena, K. Possibilities of using UAVs in pre-hospital security for medical emergencies. *Int. J. Environ. Res. Public Health* **2022**, *19*, 10754. [CrossRef]
30. Malang, C.; Charoenkwan, P.; Wudhikarn, R. Implementation and critical factors of unmanned aerial vehicle (UAV) in warehouse management: A systematic literature review. *Drones* **2023**, *7*, 80. [CrossRef]
31. Rejeb, A.; Rejeb, K.; Simske, S.J.; Treiblmaier, H. Drones for supply chain management and logistics: A review and research agenda. *Int. J. Logist. Res. Appl.* **2023**, *26*, 708–731. [CrossRef]
32. Wulfovich, S.; Rivas, H.; Matabuena, P. Drones in healthcare. In *Digital Health: Scaling Healthcare to the World*; Springer: Cham, Switzerland, 2018; pp. 159–168.
33. Sigari, C.; Biberthaler, P. Medical drones: Disruptive technology makes the future happen. *Unfallchirurg* **2021**, *124*, 974. [CrossRef]
34. Jack, C.A. Life Cycle Cost Model for Transit Bus Fleets. Master's Thesis, West Virginia University, Morgantown, WV, USA, 2024.
35. Kuru, K. Planning the future of smart cities with swarms of fully autonomous unmanned aerial vehicles using a novel framework. *IEEE Access* **2021**, *9*, 6571–6595. [CrossRef]
36. Lambert, T. Optimization of Drone Routing for Humanitarian Applications. Master's Thesis, University of Liège, Liège, Belgium, 2019.
37. Wu, J.; Ye, Y.; Du, J. Multi-objective reinforcement learning for autonomous drone navigation in urban areas with wind zones. *Autom. Constr.* **2024**, *158*, 105253. [CrossRef]
38. Iqab, M. Harnessing Drones for Faster, Cheaper, Greener Logistic Solutions in Challenging Environments. Master's Thesis, LAB University of Applied Sciences, Lahti, Finland, 2024.
39. Naz, A.; Hoque, I. Data collection technologies and their utilization in intelligent transportation systems: An overview. In Proceedings of the 7th International Conference on Civil Engineering for Sustainable Development (ICCESD 2024), KUET, Khulna, Bangladesh, 7–9 February 2024.
40. Claesson, A.; Svensson, L.; Nordberg, P.; Ringh, M.; Rosenqvist, M.; Djarv, T.; Samuelsson, J.; Hernborg, O.; Dahlbom, P.; Jansson, A.; et al. Drones may be used to save lives in out of hospital cardiac arrest due to drowning. *Resuscitation* **2017**, *114*, 152–156. [CrossRef]
41. Greenwood, W.W.; Lynch, J.P.; Zekkos, D. Applications of UAVs in civil infrastructure. *J. Infrastruct. Syst.* **2019**, *25*, 04019002. [CrossRef]
42. Magnusson, S.; Hagerfors, P.P. Drone Deliveries of Medical Goods in Urban Healthcare. Master's Thesis, Chalmers University of Technology, Gothenburg, Sweden, 2019.

43. Stokenberga, A.; Ochoa, M.C. *Unlocking the Lower Skies: The Costs and Benefits of Deploying Drones Across Use Cases in East Africa*; World Bank Publications: Washington, DC, USA, 2021.
44. Quintanilla García, I.; Vera Velez, N.; Alcaraz Martínez, P.; Vidal Ull, J.; Fernandez Gallo, B. A quickly deployed and UAS-based logistics network for delivery of critical medical goods during healthcare system stress periods: A real use case in Valencia (Spain). *Drones* **2021**, *5*, 13. [CrossRef]
45. Cheema, M.A.; Ansari, R.I.; Ashraf, N.; Hassan, S.A.; Qureshi, H.K.; Bashir, A.K.; Politis, C. Blockchain-based secure delivery of medical supplies using drones. *Comput. Netw.* **2022**, *204*, 108706. [CrossRef]
46. Poljak, M.; Šterbenc, A.J.C.M. Use of drones in clinical microbiology and infectious diseases: Current status, challenges and barriers. *Clin. Microbiol. Infect.* **2020**, *26*, 425–430. [CrossRef] [PubMed]
47. Elsanhoury, M.; Mäkelä, P.; Koljonen, J.; Välisuo, P.; Shamsuzzoha, A.; Mantere, T.; Elmusrati, M.; Kuusniemi, H. Precision positioning for smart logistics using ultra-wideband technology-based indoor navigation: A review. *IEEE Access* **2022**, *10*, 44413–44445. [CrossRef]
48. Quamar, M.M.; Al-Ramadan, B.; Khan, K.; Shafiullah, M.; El Ferik, S. Advancements and applications of drone-integrated geographic information system technology—A review. *Remote Sens.* **2023**, *15*, 5039. [CrossRef]
49. Matthew, U.O.; Kazaure, J.S.; Amaonwu, O.; Adamu, U.A.; Hassan, I.M.; Kazaure, A.A.; Ubochi, C.N. Role of internet of health things (IoHTs) and innovative internet of 5G medical robotic things (IIo-5GMRTs) in COVID-19 global health risk management and logistics planning. In *Intelligent Data Analysis for COVID-19 Pandemic*; Springer: Singapore, 2021; pp. 27–53.
50. Konert, A.; Smereka, J.; Szarpak, L. The use of drones in emergency medicine: Practical and legal aspects. *Emerg. Med. Int.* **2019**, *2019*, 3589792. [CrossRef]
51. Ghelichi, Z.; Gentili, M.; Mirchandani, P.B. Mirchandani. Logistics for a fleet of drones for medical item delivery: A case study for Louisville, KY. *Comput. Oper. Res.* **2021**, *135*, 105443. [CrossRef]
52. Molinari, S.; Patriarca, R.; Ducci, M. The Challenges of Blood Sample Delivery via Drones in Urban Environment: A Feasibility Study through Specific Operation Risk Assessment Methodology. *Drones* **2024**, *8*, 210. [CrossRef]
53. Bor-Yaliniz, I.; Salem, M.; Senerath, G.; Yanikomeroglu, H. Is 5G ready for drones: A look into contemporary and prospective wireless networks from a standardization perspective. *IEEE Wirel. Commun.* **2019**, *26*, 18–27. [CrossRef]
54. Galvan-Tejada, G.M.; Aguilar-Torrentera, J. 5G Connectivity for Aerial Scenarios: A New Spatial and Temporal Perspective for Wireless Networks. In Proceedings of the 2021 18th International Conference on Electrical Engineering, Computing Science and Automatic Control (CCE), Mexico City, Mexico, 10–12 November 2021; IEEE: Piscataway, NJ, USA, 2021.
55. Alhafnawi, M.; Salameh, H.A.B.; Masadeh, A.; Al-Obiedollah, H.; Ayyash, M.; El-Khazali, R.; Elgala, H. A survey of indoor and outdoor uav-based target tracking systems: Current status, challenges, technologies, and future directions. *IEEE Access* **2023**, *11*, 68324–68339. [CrossRef]
56. Neal, A.D.; Sharpe, R.G.; Conway, P.P.; West, A.A. smaRTI—A cyber-physical intelligent container for industry 4.0 manufacturing. *J. Manuf. Syst.* **2019**, *52*, 63–75. [CrossRef]
57. Pirri, A.; Tortora, G.; Niglio, F. Autonomous Drones and Smart Containers in Medicine. In *Applying Drones to Current Societal and Industrial Challenges*; Springer Nature: Cham, Switzerland, 2024; pp. 255–272.
58. Alquwayzani, A.A.; Albuali, A.A. A Systematic Literature Review of Zero Trust Architecture for UAV Security Systems in IoBT. *Preprints* **2024**, 2024030349. [CrossRef]
59. Alotaibi, F.M.; Al-Dhaqm, A.; Al-Otaibi, Y.D.; Alsewari, A.A. A comprehensive collection and analysis model for the drone forensics field. *Sensors* **2022**, *22*, 6486. [CrossRef]
60. Kafi, A.H.; Monowar, M.I.; Antara RS, I.; Maruf, M.M. UAV Based Remote Sensing for Developing Countries. Ph.D. Dissertation, BRAC University, Dhaka, Bangladesh, 2015.
61. Tazrin, T.; Fouda, M.M.; Fadlullah, Z.M.; Nasser, N. UV-CDS: An energy-efficient scheduling of UAVs for premises sterilization. *IEEE Trans. Green Commun. Netw.* **2021**, *5*, 1191–1201. [CrossRef]
62. Bassi, E. European drones regulation: Today's legal challenges. In Proceedings of the 2019 International Conference on Unmanned Aircraft Systems (ICUAS), Atlanta, GA, USA, 11–14 June 2019; IEEE: Piscataway, NJ, USA, 2019.
63. Huttunen, M. Civil unmanned aircraft systems and security: The European approach. *J. Transp. Secur.* **2019**, *12*, 83–101. [CrossRef]
64. De Schrijver, S. Commercial use of drones: Commercial drones facing legal turbulence: Towards a new legal framework in the EU. *US-China Law Rev.* **2019**, *16*, 338. [CrossRef]
65. Clarke, R.; Moses, L.B. The regulation of civilian drones' impacts on public safety. *Comput. Law Secur. Rev.* **2014**, *30*, 263–285. [CrossRef]
66. Cavoukian, A. *Privacy and Drones: Unmanned Aerial Vehicles*; Information and Privacy Commissioner of Ontario: Ontario, ON, Canada, 2012.
67. Edemekong, P.F.; Annamaraju, P.; Haydel, M.J. *Health Insurance Portability and Accountability Act*; ASPE: Raleigh, NC, USA, 2018.
68. Finn, R.L.; Wright, D. Unmanned aircraft systems: Surveillance, ethics and privacy in civil applications. *Comput. Law Secur. Rev.* **2012**, *28*, 184–194. [CrossRef]
69. Balasingam, M. Drones in medicine—The rise of the machines. *Int. J. Clin. Pract.* **2017**, *71*, e12989. [CrossRef] [PubMed]
70. Hassanalian, M.; Abdelkefi, A. Classifications, applications, and design challenges of drones: A review. *Prog. Aerosp. Sci.* **2017**, *91*, 99–131. [CrossRef]

71. Thomas, P.R.; Takahashi, T.T. The Wild West of Aviation: An Overview of Unmanned Aircraft Systems Regulation in the United States. In Proceedings of the AIAA Scitech 2020 Forum, Orlando, FL, USA, 6–10 January 2020.
72. Salinas, J.C.; Lewandowski, T. Blue Unmanned Aircraft Systems Explained: The Current Drone Market, Flight Regulations, and Debunking Common Misconceptions. *Transp. Res. Rec.* **2024**. [CrossRef]
73. Wanyonyi Rodgers, M. Legal, Policy and Institutional Framework for Regulation of UAS in the United States of America (USA). In *The Law Regulating Unmanned Aircraft Systems in the United States, South Africa and Kenya: A Civil Aviation Perspective*; Springer Nature: Cham, Switzerland, 2024; pp. 81–120.
74. Rushiti, V.; Kulakov, A.; Stojkoska, B.R. An Overview of UAS Regulations in the European Union and the Balkan Region. In Proceedings of the 2024 47th MIPRO ICT and Electronics Convention (MIPRO), Opatija, Croatia, 20–24 May 2024; IEEE: Piscataway, NJ, USA, 2024.
75. Konert, A.; Kasprzyk, P. Very Low Level Flight Rules for Manned and Unmanned Aircraft Operations. *J. Intell. Robot. Syst.* **2024**, *110*, 1–8. [CrossRef]
76. Aggarwal, S.; Balaji, S.; Gupta, P.; Mahajan, N.; Nigam, K.; Singh, K.J.; Bhargava, B.; Panda, S. Enhancing Healthcare Access: Drone-based Delivery of Medicines and Vaccines in hard-to-Reach Terrains of Northeastern India. *Prev. Med. Res. Rev.* **2024**, *1*, 172–178. [CrossRef]
77. Sharma, S.; Sharma, H. Drone a technological leap in health care delivery in distant and remote inaccessible areas: A narrative review. *Saudi J. Anaesth.* **2024**, *18*, 95–99. [CrossRef]
78. Zailani, M.A.H.; Sabudin, R.Z.A.R.; Rahman, R.A.; Saiboon, I.M.; Ismail, A.; Mahdy, Z.A. Drone for medical products transportation in maternal healthcare: A systematic review and framework for future research. *Medicine* **2020**, *99*, e21967. [CrossRef]
79. Wang, N. We Live on Hope. . .: Ethical Considerations of Humanitarian Use of Drones in Post-Disaster Nepal. *IEEE Technol. Soc. Mag.* **2020**, *39*, 76–85. [CrossRef]
80. Berninzon, A.L.; Vongasemjit, O. Potential Benefits of Drones for Vaccine Last-Mile Delivery in Nepal. Master's Thesis, Massachusetts Institute of Technology, Cambridge, MA, USA, 2021.
81. Demuyakor, J. Ghana go digital Agenda: The impact of zipline drone technology on digital emergency health delivery in Ghana. *Humanities* **2020**, *8*, 242–253. [CrossRef]
82. Erdelj, M.; Natalizio, E. UAV-assisted disaster management: Applications and open issues. In Proceedings of the 2016 International Conference on Computing, Networking and Communications (ICNC), Kauai, HI, USA, 15–18 February 2016; IEEE: Piscataway, NJ, USA, 2016.
83. Boger, R.; Low, R.; Nelson, P. Identifying hurricane impacts on Barbuda using citizen science ground observations, drone photography and satellite imagery. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2020**, *42*, 23–28. [CrossRef]
84. Cruz, S.; Orlando, N. Low-Cost UAV Applications in Urban Change and Damage Assessment: Study on Richards Coastal Community in Post-Hurricane Irma-Maria Loíza, PR. Master's Thesis, Polytechnic University of Puerto Rico, San Juan, Puerto Rico, 2017.
85. Chowdhury, S.; Emelogu, A.; Marufuzzaman, M.; Nurre, S.G.; Bian, L. Drones for disaster response and relief operations: A continuous approximation model. *Int. J. Prod. Econ.* **2017**, *188*, 167–184. [CrossRef]
86. Damoah, I.S.; Ayakwah, A.; Tingbani, I. Artificial intelligence (AI)-enhanced medical drones in the healthcare supply chain (HSC) for sustainability development: A case study. *J. Clean. Prod.* **2021**, *328*, 129598. [CrossRef]
87. Comtet, H.E.; Johannessen, K.-A. A socio-analytical approach to the integration of drones into health care systems. *Information* **2022**, *13*, 62. [CrossRef]
88. Awad, A.; Trenfield, S.J.; Pollard, T.D.; Ong, J.J.; Elbadawi, M.; McCoubrey, L.E.; Goyanes, A.; Gaisford, S.; Basit, A.W. Connected healthcare: Improving patient care using digital health technologies. *Adv. Drug Deliv. Rev.* **2021**, *178*, 113958. [CrossRef]
89. Siripurapu, S.; Darimireddy, N.K.; Chehri, A.; AV, P. Technological advancements and elucidation gadgets for healthcare applications: An exhaustive methodological review-part-II (robotics, drones, 3D-printing, internet of things, virtual/augmented and mixed reality). *Electronics* **2023**, *12*, 548. [CrossRef]
90. Al-Wathinani, A.M.; Alhallaf, M.A.; Borowska-Stefańska, M.; Wiśniewski, S.; Sultan, M.A.S.; Samman, O.Y.; Alobaid, A.M.; Althunayyan, S.M.; Goniewicz, K. Elevating healthcare: Rapid literature review on drone applications for streamlining disaster management and prehospital care in Saudi Arabia. *Healthcare* **2023**, *11*, 1575. [CrossRef]
91. Deorankar, P.S.; Vaidya, V.V.; Munot, N.M.; Jain, K.S.; Patil, A.R. Optimizing Healthcare Throughput: The Role of Machine Learning and Data Analytics. In *Biosystems, Biomedical & Drug Delivery Systems: Characterization, Restoration and Optimization*; Springer Nature: Singapore, 2024; pp. 225–255.
92. Asiri, M.A.A. An Agile Data Analytics Framework to Improve Healthcare Process Performance in Infectious Disease Propagation. Ph.D. Dissertation, State University of New York at Binghamton, Binghamton, NY, USA, 2024.
93. Rawat, B.; Bist, A.S.; Apriani, D.; Permadi, N.I.; Nabila, E.A. Ai based drones for security concerns in smart cities. *APTISI Trans. Manag.* **2023**, *7*, 122–127. [CrossRef]
94. Hoang, M.L. Smart Drone Surveillance System Based on AI and on IoT Communication in Case of Intrusion and Fire Accident. *Drones* **2023**, *7*, 694. [CrossRef]
95. Shah, I.A.; Jhanjhi, N.Z.; Brohi, S.N. Use of AI-Based Drones in Smart Cities. In *Cybersecurity Issues and Challenges in the Drone Industry*; IGI Global: Hershey, PA, USA, 2024; pp. 362–380.
96. Patil, P.G.; Patil, M.M. AI and IoT-Enabled solutions for Protection of. In *Green Industrial Applications of Artificial Intelligence and Internet of Things*; Bentham Science Publishers: Sharjah, United Arab Emirates, 2024; pp. 211–225.

97. Santosh Kumar, R.; Prakash, K.L.N.; Suryanarayana, G. Drones enable IoT applications for smart cities. In *Drone Technology: Future Trends and Practical Applications*; John Wiley & Sons: Hoboken, NJ, USA, 2023; pp. 207–241.
98. Amukele, T.K.; Sokoll, L.J.; Pepper, D.; Howard, D.P.; Street, J. Can Unmanned Aerial Systems (Drones) Be Used for the Routine Transport of Chemistry, Hematology, and Coagulation Laboratory Specimens? *PLoS ONE* **2015**, *10*, e0134020. [CrossRef] [PubMed]
99. Immoos, M. Transportlogistik mit Drohnen: Nachhaltige Transporte aus der Luft. *Klin. Einkauf* **2024**, *6*, 14–16. [CrossRef]
100. Na, H.; Chang, Y.S. Study on the Policies, Regulations of Drone-Based Logistics. In Proceedings of the 2024 2nd International Conference on Cyber Resilience (ICCR), Dubai, United Arab Emirates, 26–28 February 2024; IEEE: Piscataway, NJ, USA, 2024.
101. Filippi, G.; Basu, T.; Patelli, E.; Vasile, M.; Fossati, M. A Digital Twin Model for Drone Based Distributed Healthcare Network. In Proceedings of the 33rd European Safety and Reliability Conference, Southampton, UK, 3–8 September 2023.
102. Emad Alfaris, R.; Vafakhah, Z.; Jalayer, M. Application of Drones in Humanitarian Relief: A Review of State of Art and Recent Advances and Recommendations. In *Transportation Research Record*; Sage Publications: Oaks, CA, USA, 2023; pp. 689–705. [CrossRef]
103. Li, F.; Kunze, O. A comparative review of air drones (UAVs) and delivery bots (SUGVs) for automated last mile home delivery. *Logistics* **2023**, *7*, 21. [CrossRef]
104. Atiga, O.; Tanzubil, B.J.; Asaana, J.; Ayamba, E.C.; Seidu, M.T.; Mohammed, I. Shortening The Last-Mile: Impact of Zipline Medical Drone Delivery on The Operations of Hard-to-Reach Healthcare Facilities in Northern Ghana. *Afr. J. Appl. Res.* **2024**, *10*, 178–200. [CrossRef]
105. Griffith, E.F.; Schurer, J.M.; Mawindo, B.; Kwibuka, R.; Turibyarive, T.; Amuguni, J.H. The use of drones to deliver rift valley fever vaccines in Rwanda: Perceptions and recommendations. *Vaccines* **2023**, *11*, 605. [CrossRef]
106. Mihigo, D.; Lukenangula, J.M. The Role of Drone Technology for future Smart City Concept Implementation in Developing World. The Case of Kigali City-Rwanda. *ASRIC J. Nat. Sci.* **2023**, *3*, 198–209.
107. Burchardt, M.; Umlauf, R. Dreams and realities of infrastructural leapfrogging: Airspace, drone corridors, and logistics in African healthcare. In *Making Spaces through Infrastructure*; De Gruyter Oldenbourg: Berlin, Germany, 2023; pp. 221–240.
108. Dukkanci, O.; Koberstein, A.; Kara, B.Y. Drones for relief logistics under uncertainty after an earthquake. *Eur. J. Oper. Res.* **2023**, *310*, 117–132. [CrossRef]
109. German Congress of Laboratory Medicine: 19th Annual Congress of the DGKL and 6th Symposium of the Biomedical Analytics of the DVTA e. V. together with the 6th German POCT-Symposium: Bremen, Germany, September 25–27, 2024. *J. Lab. Med.* **2024**, *48*, eA1–eA88. [CrossRef]
110. Available online: https://jedsy.com/ (accessed on 1 August 2024).
111. Available online: https://swoop.aero/ (accessed on 1 August 2024).
112. Bücheler, T. Drohnen und Künstliche Intelligenz in der Bauindustrie. In *Künstliche Intelligenz im Bauwesen: Grundlagen und Anwendungsfälle*; Springer Fachmedien: Wiesbaden, Germany, 2024; pp. 431–445.
113. Amirsahami, A.; Barzinpour, F.; Pishvaee, M.S. A hierarchical model for strategic and operational planning in blood transportation with drones. *PLoS ONE* **2023**, *18*, e0291352. [CrossRef]
114. Harshe, S.; Trostle, G.; Teoh, R. *Drone Medical Deliveries in Low and Moderate Income Countries: Insights from Vanuatu, Malawi, Rwanda, and Ghana*; NASA Aeronautics Research Institute: Mountain View, CA, USA, 2020.
115. Stierlin, N.; Loertscher, F.; Renz, H.; Risch, L.; Risch, M. A Green Laboratory Approach to Medical Sample Transportation: Assessing the Carbon Dioxide (CO_2) Footprint of Medical Sample Transportation by Drone, Combustion Car, and Electric Car. *Drones* **2024**, *8*, 489. [CrossRef]
116. Stierlin, N.; Loertscher, F.; Renz, H.; Risch, L.; Risch, M. Preanalytic Integrity of Blood Samples in Uncrewed Aerial Vehicle (UAV) Medical Transport: A Comparative Study. *Drones* **2024**, *8*, 517. [CrossRef]