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INTERCONNECTED IMPACTS OF COVID-19 ON HUMAN AND ANIMAL HEALTH SYSTEMS

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Abstract
This review explores the multifaceted impacts of the COVID-19 pandemic on both human and animal health, emphasizing the zoonotic transmission of SARS-CoV-2, disruptions in veterinary services, and the crucial role of animal models in studying long-term immune responses and chronic conditions such as Long COVID. It examines how human–wildlife interactions contributed to the zoonotic spillover of SARS-CoV-2 and evaluates the effects of pandemic restrictions on veterinary care and animal welfare. Recent research is analyzed to highlight the challenges faced by veterinary professionals, including reduced disease surveillance and compromised management capacities, with broader implications for animal health and welfare. The review also discusses the use of animal models—such as hamsters and non-human primates—in investigating viral persistence and immune mechanisms, underscoring their importance in developing therapeutic strategies for both humans and animals. Furthermore, it identifies significant knowledge gaps regarding the long-term effects of COVID-19 in animals and inconsistent evidence on reverse zoonotic transmission. By synthesizing current findings, this review advocates for future research grounded in the One Health framework to strengthen interdisciplinary collaboration and enhance preparedness against emerging zoonotic threats.

1. INTRODUCTION

The COVID-19 pandemic is a poignant example of the severe effects of zoonoses on human and animal health, underscoring the importance of a single health approach. These approaches, which recognize the interconnectedness between human health, veterinary medicine, and environmental conservation, are crucial for controlling ongoing and future pathogens with zoonotic potential and the ability to cross species barriers(Verma et al., 2024). SARS-CoV-2 is thought to have emerged from animal reservoirs, which further highlights the significance of health. The scale of the pandemic has driven a focus on pathways for zoonotic transmission, disruption to veterinary services, and long-term consequences for animal health(Čítek et al., 2022). However, an extended body of knowledge regarding the zoonotic dimensions of COVID-19(Ghai et al., 2022). The gaps still need to be found, especially regarding the long-term impacts on animals and whether veterinary systems are resilient to significant public health emergencies. In summary, this review intends to consolidate the existing literature to elucidate these overlapping problems - the implications of zoonotic transmission, veterinary service bottlenecks, and experimental animal models employed for studying post-acute sequelae. It is a call to action, emphasizing the importance of the One Health approach and the audience's role in promoting this interdisciplinary approach(Horefti, 2023).

Emerging zoonotic threats have highlighted the increasing relevance of the One Health approach, which links human, animal, and environmental health. For example, studies have shown that wildlife markets and human encroachment into natural ecosystems can significantly increase the odds of zoonotic spillover(Verma et al., 2024).. However, while these studies have enhanced our understanding of zoonotic origins and wildlife, they have not filled a critical knowledge void regarding the impact of sustained disruptions to veterinary services on animal welfare and disease surveillance. Filling this gap is essential to bolster pandemic preparedness for both humans and animals(Espinosa García-San Román et al., 2023). This review seeks to address this deficiency by delivering an exhaustive examination of COVID-19's influence on zoonotic transmission, veterinary services, and the application of animal models in the investigation of chronic illnesses like COVID. This review summarizes recent research on zoonotic diseases and the challenges confronting veterinary services during pandemics, addressing these limitations while providing insights into how integrating human and animal health strategies can reduce future pandemic risks and enhance global health outcomes(Erkyihun and Alemayehu, 2022).

Table 1: Summary of Key Sections and Findings in the Review Paper

Section	Key Points	Findings/Insights
Zoonotic Transmission of SARS-CoV-2	- Human-wildlife interactions contribute to zoonotic spillover - Role of wildlife reservoirs (bats, minks, etc.)	- Wildlife plays a key role in the emergence of SARS-CoV-2 - Need for better wildlife surveillance to prevent zoonotic events
Impact of COVID-19 on Veterinary Services	- Pandemic restrictions reduced access to veterinary care - Implications for livestock and companion animal health	- Reduced surveillance led to diminished disease control in livestock - Delayed veterinary care impacts animal welfare
Animal Models in Studying SARS-CoV-2	- Use of hamsters, ferrets, and non-human primates - Study of viral persistence, immune response, and Long COVID	- Animal models provide critical insights into long-term health impacts - They are essential for testing vaccines and treatments
One Health Approach	- Integration of human, animal, and environmental health - Interdisciplinary collaboration in pandemic preparedness	- One Health approach is key to mitigating future zoonotic risks - Need for stronger policy and research integration
Knowledge Gaps	- Long-term effects of COVID-19 in animals - Inconsistent research on reverse zoonotic transmission	- Lack of data on animal reservoirs of SARS-CoV-2 - Need for more longitudinal studies on animal health impacts
Future Research Directions	- Long-term surveillance of wildlife and animal health - Stronger veterinary systems during crises	- Focus on preventive strategies - Integration of One Health to manage zoonotic diseases and improve global health resilience

2. The Role of Zoonotic Transmission in the Emergence of COVID-19

2.1 Zoonotic Origins of SARS-CoV-2 and Related Coronaviruses

Interest in zoonoses (diseases that can pass from animals to humans) and their origins has been reinvigorated by the emergence of SARS-CoV-2, the virus responsible for COVID-19. SARS-CoV-2 is thought to be bat-derived, and as with SARS-CoV and MERS-CoV, the virus was identified in the environment associated with zoonotic spillover events(Verma et al., 2024). Other species, such as pangolins and minks, contribute to the transmission dynamics between animal reservoirs of alpha coronaviruses, but bats are the primary reservoir. Bats have a massive reservoir of coronaviruses, such as the analysis of a bat virus (RaTG13) from Rhinolophus affinis bats, which indicates 96% genomic similarity to SARS-CoV-2, suggesting that the original host may be bats(Do et al., 2021). However, how the virus is transmitted from animals to humans is unclear, although pangolins have been identified as possible intermediate hosts based on the similarities between the receptor-binding domains that facilitate human infections(Do et al., 2021).

The zoonotic origins of earlier outbreaks were more straightforward than those of SARS and MERS. Civet cats that serve as intermediaries between bats and humans were found to be a source of SARS-CoV, and dromedary camels have been implicated in the transmission of MERS-CoV.2 Here, and the diversity of intermediate hosts between various coronaviruses exemplifies the complexity and heterogeneity seen in zoonotic spillover pathways(Bitaraf sani et al., 2023). Various forms of human-wildlife interactions, including wildlife trade, habitat encroachment, and agricultural practices, are essential for zoonotic spillovers. Because it sells live animals, the Huanan Seafood Wholesale Market in Wuhan, China was first suspected to be a transmission site for SARS-CoV-2. Markets where human and animal contact is always close provide platforms for cross-species pathogen transmission(Verma et al., 2024).

The approaches used during SARS and MERS focused heavily on conventional epidemiological methods, such as contact tracing and case investigations, to delineate the transmission pathways. Less prevalent than the COVID-19 pandemic, genetic analysis has also been applied(Dharmarajan et al., 2022). During the COVID-19 pandemic, this was accelerated by rapid genomics sequencing advancements, which provided rapidly available data on viral mutations, facilitated real-time analysis, and allowed unprecedented details regarding transmission dynamics. Metagenomics provides further insights by determining viral sequences in animal species and separating possible reservoirs. In targeted studies, including those in wet markets, these approaches were used to quickly map mutations and identify virus reservoirs in an unprecedented manner compared to what was available during the SARS and MERS outbreaks(Sievers et al., 2024).

The zoonotic origins of SARS-CoV-2 emphasize the intricate relationship between wildlife and human health. Advancements in research methodologies such as genomic sequencing and metagenomics have significantly improved our understanding of zoonotic spillovers, underscoring the importance of continued surveillance and collaborative research to prevent future pandemics(Sánchez et al., 2024).

2.2 Wildlife Reservoirs and Intermediate Hosts

Decades of research on other coronaviruses can shed light on the origin and dynamics of SARS-CoV-2 transmission. This virus emerged at the end of 2019 and has continued to cause a global pandemic. An essential part of this investigation is to look for wildlife as reservoirs and possible intermediate species, which might enable the virus to jump from one host to another(Verma et al., 2024). Coronaviruses, including those phylogenetically closest to SARS-CoV-2, have been shown to have Chiroptera (bats)—exceptionally comparable free-tailed bat species–as their natural hosts. SARS-CoV-2 likely originates in a bat reservoir, as genetic analyses revealed that the RaTG13 coronavirus from Rhinolophus affinis bats is 96.2% genetically similar to SARS-CoV-2, and >96% indicates the presence of the same genome deposit between the two coronaviruses(Lytras et al., 2022). Nonetheless, direct transmission from bats to humans is unlikely due to ecological and behavioral differences between species, suggesting the presence of intermediate hosts(Deng et al., 2023).

Another area of research is on intermediate hosts, species that connect wildlife reservoirs to human populations. Since coronaviruses in pangolins have receptor-binding domains similar to those of SARS-CoV-2, pangolins have been thought to be good candidates for this role. To date, there is no strong evidence that pangolins are directly responsible for human outbreaks(Zheng et al., 2023). Ferrets are well known for their virological applications as models in the lab and provide additional evidence that SARS-CoV-2 can infect mammals. Although studies have shown that ferrets can spread the virus to other ferrets under laboratory conditions, distinguished as domesticated pets and not wildlife, the ecological role of ferrets remains uncertain(Sánchez et al., 2022).

Because of limited surveillance and the complexities of transmission chains in zoonotic disease dynamics, we have a poor understanding of how these viruses are transmitted from wildlife to humans. Differences in the roles of bats and ferrets in human outbreaks were inferred from comparative analyses of studies on these two species(Markotter et al., 2020). However, an essential portion of the research suggests that bats are likely among a wide variety of coronaviruses, but whether these species are directly implicated in the first infections in humans is truly unclear. Given their domesticated nature, ferrets are likely not major wildlife-to-human transmission players, although lab-bred ferrets can be easily infected(Gortázar et al., 2021). These studies highlight several vital gaps that need to be addressed by conducting further research in this area, allowing for a better understanding of the pathways through which zoonotic viruses pass from animal (or environmental) sources into humans. This will require improved wildlife surveillance, especially for potential intermediate host species, and interdisciplinary methods combining virology with ecology and epidemiology to identify the pathways linking wildlife and human disease. This type of research is critically important for preventing future zoonosis from occurring and for preparing the world to face public health challenges better(Vora et al., 2023).

1.3 Zoonotic Transmission Prevention Strategies

Zoonotic diseases (those transmitted from animals to humans) have substantial public health implications, especially with concerns about increasing human-animal-environment interactions. As a result, prevention strategies have transitioned to features of the One Health approach. This holistic framework recognizes that health is interconnected among humans, animals, and the environment, and urges integrated approaches across sectors to prevent health challenges at their roots(Verma et al., 2024).

Regulation of wildlife trade is a crucial One Health strategy, since illegal and unsustainable trade has been implicated in past zoonotic outbreaks, such as Ebola and SARS-CoV-2. New research has emphasized wildlife trade regulations to avoid future zoonoses. For instance, bushmeat consumption and trade have been shown to drive biodiversity loss in tropical regions and dramatically amplify the risk of zoonotic spillover risk(Vora et al., 2023). Strengthening global policies such as the Convention on International Trade in Endangered Species (CITES) and national wildlife protection laws is also critically important to reduce human contact with potential pathogens found near humans or wildlife. Tighter restrictions on wildlife markets effectively disrupt human-wildlife contact, as studies have shown after the 2003 SARS outbreak, reinforcing the need to ensure that such regulations exist not only on paper(Sievers et al., 2024).

Habitat conservation is an important aspect of zoonotic disease prevention. However, as human populations grow and natural habitats are lost, there is a greater risk of zoonotic spillover. While deforestation, urban growth, and agricultural expansion can disrupt ecosystems, they can also bring people closer to wildlife, which is a more significant opportunity for pathogens to jump. Efforts to conserve natural areas save species and limit human contact with wildlife can trigger zoonotic diseases(Leifels et al., 2022). For instance, research has revealed that preserving wetlands and forests keeps wildlife in their habitats, limiting human contact with infectious species and reducing opportunities for the spillover of diseases. In Southeast Asia, a hotspot of deforestation, targeted projects have been able to skillfully divert human-bat interactions in areas where the order Coronaviruses are often found(Sánchez et al., 2022).

These strategies align with the broader perspectives on pandemic prevention. One Health system takes an even more proactive stance, calling for surveillance systems to monitor animal health, human health, and environmental change. The integrated data from these fields will help public health officials detect zoonotic threats before they become pandemics. An example of this integration is the Global Early Warning System (GLEWS), which offers real-time monitoring of zoonotic diseases in collaboration with WHO, FAO, and OIE. It plays an essential role in surveilling zoonotic pathogens, which can be responsible for quicker actions toward any potential emergent threat(Hassan et al., 2023). The rise of COVID-19 has brought to light the necessity for everyone to work together when zoonotic pandemics emerge. International organizations, such as the World Health Organization (WHO) and the Food and Agriculture Organization, request improved intersectoral collaboration to ensure further implementation of One Health. This includes accelerating research on zoonotic pathogens, strengthening biosecurity in livestock and wildlife trade, and financing health systems that respond promptly to emerging infectious diseases(Alimi and Wabacha, 2023).

Prevention strategies developed to reduce the threat of zoonotic diseases are increasingly based on the One Health approach, which integrates human, animal, and environmental health aspects. Policy efforts can help mitigate this risk of zoonotic spillover events through wildlife trade regulations, habitat conservation actions, and other avenues(Verma et al., 2024). This provides concrete steps for using our collaborative experience across disciplines to more effectively align with a larger One Health paradigm, identify opportunities to reduce the risk of another pandemic, and safeguard these vulnerable ecosystems vital to global health(Lam et al., 2024).

3. Impact of COVID-19 on Veterinary Health Services and Animal Welfare

3.1 Disruptions in Veterinary Services and Implications for Disease Management

Veterinary services worldwide have been severely disrupted during the COVID-19 pandemic, making it even more challenging to control endemic and emerging animal diseases. The first is the access restrictions associated with lockdowns and social distancing, causing the decline of visitors to veterinary clinics as pet owners, and farmers were reluctant to come out for non-emergency treatment due to fear of contracting. It impacted habitual health assessments and immunizations, but also resulted in the postponement of timely therapy solutions for ill creatures, likely elevating morbidity or mortality experienced by household pets or farm animals(Verma et al., 2024). For example, a national American Veterinary Medical Association survey noted a 40 per cent decrease in veterinary visits during the pandemic, suggesting that many people were reluctant to access their veterinarian services(Bitaraf sani et al., 2023).

It further deepened the inequities in veterinary literature outlined throughout the pandemic, especially in rural and other underserved communities. The need for mobile clinics and outreach programs, in turn, played a vital role in managing endemic diseases among these populations. However, such initiatives were constrained operationally, further reducing the availability of preventive care. This has dire consequences for zoonotic disease control, including the essential diseases of animals or humans related to wildlife(Reaser et al., 2021). In addition, this has included impacts such as the slower expansion of the disease in livestock populations when there is a delay in routine vaccinations in areas where the disease already exists (such as foot-and-mouth disease [FMD]) and having more opportunity for an outbreak if containment or vaccination fails to occur in the early phases of an epidemic(Bitaraf sani et al., 2023).

The disruption to surveillance capabilities during the pandemic has translated into long-term impacts on disease prevention programs. Fewer veterinary visits and poor reporting of animal health issues mean that there are more opportunities to monitor or respond to disease outbreaks. Such a gap in surveillance not only hampers an effective response to known diseases, but also fosters the emergence of new pathogens(Sievers et al., 2024). The World Organization for Animal Health (OIE) warned against the overhead effects of any reduction in disease surveillance, especially in areas where new zoonotic viruses are likely to emerge, such as Southeast Asia. Declining vaccination rates and building disease reservoirs are associated with continued risk; these surveillance gaps could result in a lag in response to future outbreaks(Saba Villarroel et al., 2023).

Several research methods have been used to evaluate the consequences of these disruptions, the most common of which are professional surveys and longitudinal studies. Qualitative information on the effects of the pandemic on service delivery and animal health was acquired through surveys distributed among veterinarians and other animal health professionals. The results of these surveys demonstrate that some drivers will inform crisis management strategies, such as financial pressure, changes in operations, and the reconfiguration of service models(Steffey et al., 2023). For instance, survey results from the UK found that 70% of veterinary practices had to switch to telemedicine services (which, although beneficial, restricted physical examinations and accurate diagnostic capabilities)(Owczarczak-Garstecka et al., 2022).

On the other hand, longitudinal studies monitoring animal disease outbreaks related to lockdowns have offered a quantitative assessment of the relationship between decreased veterinary service provision and disease incidence. Research that monitored time trends in rabies vaccination coverage in India reported a steep reduction in vaccinations, which caused an increase in rabies incidence during the lockdown period(Verma et al., 2024). Through a longitudinal analysis of these trends, researchers could put together a clearer picture of how the pandemic influenced disease dynamics, and they highlighted the importance of preserving solid veterinary services even during global emergencies. This ensures a robust infrastructure and surveillance system for veterinary service delivery capable of withstanding future adversity imperative(Sievers et al., 2024). Combining qualitative data from professional surveys and longitudinal quantitative reports will encourage practices in the veterinary domain that create solidified frameworks for diverse disease management in light of other unfortunate crises, such as COVID-19(Verma et al., 2024).

3.2 Effects of the Pandemic on Animal Welfare: Livestock and Pets

The devastation caused by animal husbandry, livestock management, and companion animal care owing to the COVID-19 pandemic is a stark reality. When the virus spread worldwide, governments imposed measures to control it, and we soon began to see its impact on animal welfare. These include limited access to veterinary services, labor shortages, and increased animal welfare concerns(Verma et al., 2024). The immediate effects of the pandemic include limited access to veterinary care. Due to the resultant closure of many clinics or reduced hours for practice, routine check-ups and vaccinations were postponed, while emergency treatments were kept for livestock and pets. The American Veterinary Medical Association conducted a survey on pet care during the COVID-19 pandemic, indicating that 40% of veterinary practices noted a sharp decline in routine visits. Unable to treat their animals, pet owners failed to address ongoing issues, as dental disease and long-term illnesses went undiagnosed or untreated(Rahman et al., 2022). Similarly, livestock producers struggled to keep herds healthy when preventive care was interrupted. In New Zealand, a study found an increase in livestock deaths due to a lack of access to veterinary services for disease prevention(Abdalla et al., 2023). Labor shortages compounded these challenges in addition to access limits: lockdowns and fear of the virus limited the availability of agricultural workers, causing livestock neglect. In turn, this scarcity has adversely affected feeding, accommodation, and general management practices to the extent that stress and poor living conditions for livestock have exacerbated(Kitessa et al., 2023). For example, in Germany, a study showed that processing is delayed when poultry farms have insufficient staff, and diseases are more likely to spread due to crowding. One of the biggest challenges in companion animal care is restricted movement, which leads to fewer opportunities for exercise and socialization for pets, contributing to problem behaviors such as separation anxiety and destroying items(Boardman and Farnworth, 2022).

These disruptions to animal welfare, the impact of which may play out over the mid-to-long term, are a cause for concern. Decreasing visits to veterinarians may increase the potential for chronic health problems among pets and livestock. How animals are psychologically impacted by a lack of human interaction and living conditions cannot be ignored. Animals that had been handled more frequently in the past, such as companion dogs and dairy cows, exhibited higher levels of anxiety and stress when lockdown began(Bitaraf sani et al., 2023). Research has shown that these psychological stresses are expressed as chronic behavioral abnormalities and loss of performance, especially in the case of livestock, because stress directly influences reproductive performance and milk production(Padmanabhanunni et al., 2023).

Other studies underscore that the pandemic has worsened the existing weaknesses in animal care systems. One study in the UK showed that more than 60% of all pet owners said their pets were having more behavior issues now due to the lockdown – less socialization and exercise(Brand et al., 2023). Conversely, other researchers have argued that the pandemic has heightened the awareness of animal welfare. As many more individuals began working from the house, it gave family pet proprietors extra time to be with their four-legged close friends, and they supported greater connection with pet dogs and consequently improved care. The increase in telemedicine services also helped lessen the impact of these declines as veterinarians transitioned to providing remote consultations(Becker et al., 2023).

The COVID-19 crisis has caused numerous hurdles to livestock rearing and companion animal care. A profound reduction in access to veterinary services and labor shortages will have lasting effects on the management of these animals. Tackling these challenges will require a concerted focus on enhancing the robustness of veterinary systems and remote delivery. This crisis also presents an opportunity for innovation in the remote delivery of veterinary services, inspiring hope for the future of animal care in the face of global crises(Steffey et al., 2023).

3.3 Role of Veterinary Professionals in Pandemic Preparedness

Veterinary professionals must participate in pandemic preparedness and control (particularly in surveillance, diagnostics, and their place within One Health task force). One Health, involving human health (and disease), animal health (and disease), and the environment, is a concept that veterinarians are very well aware of, as they highlight the necessity of working jointly with public health officials and environmental scientists(Bitaraf sani et al., 2023). For instance, effective surveillance systems that monitor animal populations for emerging diseases can provide early warning signs for environmentally induced zoonoses. Veterinarians play a critical role in poultry population surveillance and the detection of disease hotspots during H5N1 avian influenza outbreaks. By using their expertise in animal health, vets can identify pathogens that threaten people and improve overall pandemic preparedness(Szablewski et al., 2023).

The recent experience with the H1N1 influenza outbreak and the COVID-19 pandemic shows that veterinarians need to be at the front of the crisis management table. During the COVID-19 pandemic, veterinarians were instrumental in understanding the potential animal-to-human transmission. Such experiences have amplified the need for visionary veterinary services that respond promptly to emerging health challenges. This means investing in training, resources, and infrastructure to ensure that veterinarians are prepared to serve interdisciplinary pandemic response teams(Deng et al., 2023). The challenges of controlling foot-and-mouth disease outbreaks in livestock have given veterinarians the necessary experience in preventing the spread of highly contagious diseases using measures that include movement restrictions, vaccination programs, and biosecurity, all of which are directly transferrable to human pandemics(Verma et al., 2024).

Newer research has promoted the integration of veterinarians into multidisciplinary pandemic response teams, as veterinarians have a distinct perspective on transdisciplinary changes to zoonoses and the management of animal health(Limper et al., 2021). According to Chan et al. (2021), veterinary professionals play an essential role in global surveillance systems because of their expertise in zoonotic diseases represented through innate human-animal interactions; thus, they are vital for recognizing imminent pandemic threats. Veterinary experience in controlling small ruminant epidemic outbreaks teaches us important lessons about quarantine strategies, available vaccination tools,

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and ongoing public education, the latter of which is often poorly perceived(Verma et al., 2024). For instance, the role of mass immunization campaigns run for livestock vaccination programmes has shown global leaders what is needed and how it can be modified to prepare humans against any pandemic among different populations. Veterinary professionals are critical contributors to pandemic preparedness, within a single health framework. Strengthening veterinary services, creating more effective surveillance systems, and establishing veterinarians among interdisciplinary response teams would enable better responses to future pandemics(Deng et al., 2023).

4. Cross-Species Transmission and Long-Term Health Impacts of COVID-19

4.1 Interspecies Transmission and Human-to-Animal Spread

Since then, SARS-CoV-2 has been capable of cross-species transmission, which is a significant source of concern, such as transmission to other animals. This suggests a species jump potential of the virus, which could signify zoonotic reverse transmission potential, namely, animal-to-human transmission(Zheng et al., 2023). Previous studies have indicated a high rate of SARS-CoV-2 infection among certain animal species, such as cats and dogs, in both domestic settings. Park et al. (2024) showed that a handful of cats and dogs become infected near human patients. These cases highlight the risk of human-to-pet transmission; however, it is currently unknown whether transmission from pets to humans is expected. Viral genetic analyses of these pets showed great closeness to human strains, indicating that transmission is likely to occur, but the risk of spillback remains relatively low(Verma et al., 2024).

Wildlife has also been suspected of transmitting SARS-CoV-2. Outbreaks have also been documented among populations of white-tailed deer in North America, suggesting that the virus is circulating within(Sánchez et al., 2024). Verma et al. (2024) found widespread infections in deer populations around the country, which could act as wildlife reservoirs for the virus. This is concerning because it could potentially result in reverse transmission to humans, especially where human-wildlife interaction is maximal, such as in hunting or rural settlements.

Reverse zoonotic transmission has become a significant concern, especially for farmed species such as minks. The transmission of SARS-CoV-2 among minks is expected to occur in numerous outbreaks within mink farms in Denmark, the Netherlands, and Spain in 2020. Importantly, research has shown that infected minks can reinfect humans, and cases of human-mink-human transmission have been recorded. These were included in a report from the European Centre for Disease Prevention and Control, which noted that intensive farming, in which humans and animals are kept close together, is a risk. Denmark culled millions of minks, whereas several European countries temporarily suspended mink farming(Sánchez et al., 2024).

Some studies indicate an essential risk of reverse zoonotic transmission from minks to humans, while others advise against overestimating this risk. Genetic virus variability in various species and on farms, along with population density and biosecurity measures, influences transmission probability(Mabry et al., 2023). For example, Dutch research has shown that minks can potentially infect humans, but strict biosecurity measures limit the risk of mass reverse infection. However, farm animals may allow the virus to mutate in ways that change its spreads(Sparrer et al., 2023).

Overall, the evidence of cross-species transmission of SARS-CoV-2 underscores the need for ongoing surveillance and implementation of robust biosecurity measures to prevent future outbreaks. The documented cases of human-to-animal-to-human transmission, particularly in mink farms, highlight the importance of monitoring animal populations for emerging zoonotic threats(Sparrer et al., 2023).

4.2 Long-Term Health Effects in Humans and Persistent Effects in Animals

Research on the long-term effects of COVID-19, such as Long COVID, has been conducted extensively since the advent of the pandemic, as shown in figure 1. Long COVID, officially now termed post-acute sequelae of SARS-CoV-2 infection (PASC), includes a constellation of signs and symptoms lasting weeks to months beyond the acute phase of the viral illness across multiple organ systems, including respiratory, cardiovascular, neurological, and psychological health Verma et al., 2024). Research suggests that people who test positive for COVID-19 can have Long COVID symptoms, such as fatigue, shortness of breath, cognitive impairment, and mental health issues. One example is from a large-scale study in the UK, which found that 10-30% of patients had residual symptoms several months after the resolution of the acute phase of the disease(Li et al., 2023).

There is a new but still nascent understanding that animals infected with SARS-CoV-2 may experience long-term effects. Research suggests that domestic animals, such as cats and dogs, can become infected with the virus, possibly showing respiratory signs or signs of gastrointestinal disease. Park et al. (2024) reported symptoms for weeks after infection, leading to speculation about possible long-term health effects. Nonetheless, the long-term consequences in these hosts remain largely uncharacterized. Likewise, farm animals such as minks and pigs have been identified as infected, but in-depth chronic symptom studies are still needed. Researchers in Denmark, where large outbreaks occurred at mink farms, have examined whether minks could survive without apparent illness, yet have longer-term effects like COVID in humans(Deng et al., 2023).

A significant challenge is that various species may react dissimilarly to the virus and standardized evaluation protocols are complex to establish. Another challenge is the need for standard veterinary protocols for long-term health monitoring, which makes it challenging to collect standardized data across species and populations(Bitaraf sani et al., 2023). Human patients are closely tracked according to standardized clinical protocols, whereas animals rarely receive such post-infection attention. Ethics also come into play here, where scientists must thoroughly weigh the desire to explore the question circle against animal welfare. In humans, these include clinical follow-ups, wherein patients are followed over time to observe symptoms that persist or evolve(Proal et al., 2023). Immune monitoring is also used to gain insight into the mechanisms responsible for long-term COVID, such as immune dysregulation and inflammation. These approaches broadly include patient self-reporting, clinical examination, and laboratory tests to measure markers of persistent illness. Specifically, various studies have examined cytokine profiles and inflammatory markers to characterize the chronic immune response in individuals with Long COVID individuals(Bohmwald et al., 2024).

Clinical studies in animals that examine persistent symptoms primarily rely on observational data and are less than comprehensive clinical evaluations. To study infection in humans, researchers might use an animal model; hamsters and ferrets are often used for this purpose, as they present many symptoms found in human infections; however, the behavior of animals is too complex to resemble that of the rest of their population, so these responses cannot be easily extrapolated(Paterson et al., 2023). Hamster models can mimic the most horrendous breathing problems, but pet or farm animals do not have similar long-term effects. Moreover, animal studies often have logistical limitations because we cannot easily monitor symptoms, such as fatigue or cognitive impairment, in animals(Verma et al., 2024). Humans and animals affected by SARS-CoV-2 have unique biological and ecological contexts. However, long COVID (post-acute sequelae of SARS-CoV-2 infection) research methodologies are so disparate that it needs to be clarified whether animal species could join the droves of human beings afflicted with chronic symptoms. There is a pressing need for such expanded work on animal health after infection to assess whether effects manifest across species, and if veterinary recommendations are needed to monitor long-term health impacts in pets and livestock(Vora et al., 2023).

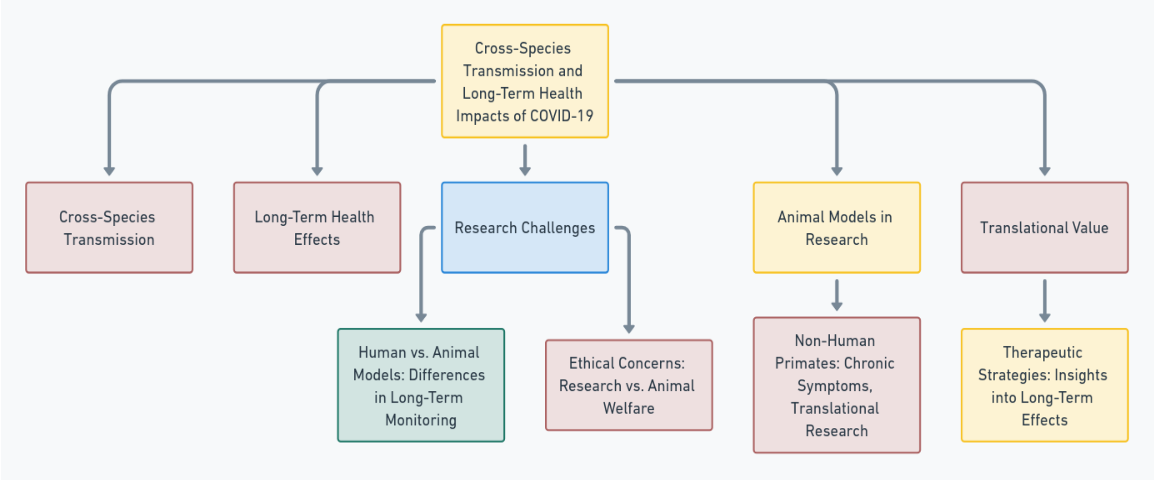

Figure 1: This flowchart illustrates the key aspects of Cross-Species Transmission and Long-Term Health Impacts of COVID-19, highlighting human-to-animal and reverse zoonotic transmission, long COVID symptoms in humans, and potential chronic effects in animals. Research challenges include differences between human and animal models and ethical concerns regarding animal welfare. Animal models, such as small mammals and non-human primates, contribute to vaccine development and understanding long-term health effects, offering translational value for therapeutic strategies and future treatments.

4.3 Utilizing Animal Models for Understanding Long-Term Effects

The fundamental feature underlying these studies is an animal model that can help us understand SARS-CoV-2 infection-associated long-lasting immune-pathogenic mechanisms leading to chronic diseases. Small animal models, such as hamsters and ferrets, and larger ones, including non-human primates, have revealed key aspects of virus-host interactions. They enable researchers to assess how viral replication, immune activation, and the potential for chronic infection progress, which is imperative for understanding diseases, including Long Covid(Verma et al., 2024).

For example, hamsters have been used extensively, as they readily become infected with SARS-CoV-2 and develop some features of human disease. Another study conducted by researchers at the University of Hong Kong utilizing Syrian hamsters provided important information on viral reservoirs and immune responses in the respiratory tract. This work has also opened the door for new vulnerable targets for human treatment to reduce viral persistence. In contrast, ferrets closely mimic human respiratory responses and serve as ideal models for investigating viral transmission dynamics and vaccine efficacy(Paterson et al., 2023). Early trials with ferrets have shown that mRNA vaccines can galvanize an immune response, directing human clinical trials should go(Leon et al., 2022).

Owing to their genetic and physiological proximity to humans, non-human primates are indispensable for the field of SARS-CoV-2 immunity. New studies extending to months following infection in rhesus macaques have shown persistent inflammatory responses that closely resemble the systemic chronic inflammation evident in many human patients with Long COVID. Such models have played a crucial role in identifying persistent viral infection biomarkers as they provide insights into chronic disease processes relevant to humans(Bohmwald et al., 2024). Additionally, NHP have been instrumental in elucidating post-acute sequelae of SARS-CoV-2 infection on the cardiovascular and neurological systems for application in therapeutic strategies targeting these symptoms in humans(Narayanan et al., 2024).

These animal models have a substantial translational value. Animal studies provide essential insights that are relevant for therapeutic strategies and vaccines in human medicine and veterinary practice(Layton et al., 2023). Studies in ferrets, for instance, have informed the development of the Pfizer-BioNTech mRNA vaccine, which has proven to be very effective against SARS-CoV-2 infection. This serves as a starting point for preclinical intervention testing before the human trial stage, emphasizing the safety and efficacy of treatment. With evolution in research, these models will continue to be critical for SARS-CoV-2 and its potential sequelae to inform public health measures and improve outcomes(Layton et al., 2023).

5. Conclusion

This review analyzed the diverse effects of COVID-19 on human and animal health, emphasizing zoonotic transmission, interruptions in veterinary services, and the use of animal models to investigate long-term immune responses and chronic illnesses such As COVID. This emphasizes the zoonotic roots of SARS-CoV-2, including the significance of wildlife reservoirs and human-animal interactions, which are essential for comprehending pandemic spillover risks. The assessment highlighted substantial disruptions to veterinary services that impacted livestock management and companion animal care during the pandemic, indicating broader consequences for animal welfare and disease surveillance. Moreover, animal models, such as hamsters, ferrets, and non-human primates, have been crucial for enhancing the comprehension of viral reservoirs and immune responses, thereby aiding therapeutic options for both human and veterinary health. Nonetheless, some deficiencies persist, notably the absence of longitudinal studies regarding the health effects of SARS-CoV-2 in animals and inconsistent investigations of reverse zoonotic transmission. Moreover, interruptions in veterinary services during the pandemic have highlighted the need for more robust systems to uphold animal welfare and disease management during emergencies. Subsequent research should concentrate on longitudinal studies monitoring the enduring effects of the virus in animals, enhanced wildlife surveillance, and the application of animal models to optimize therapeutic strategies. Despite these limitations, this analysis underscores the significance of the One Health concept, which integrates human, animal, and environmental health perspectives to improve pandemic preparedness. These findings enhance the understanding of the interdependence of health systems and the necessity for interdisciplinary collaboration to reduce future zoonotic hazards and protect world health.

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