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Review Paper

Comparison of the Genotypes of the West Nile Virus Identified in Iran and Neighboring Countries

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ABSTRACT

West Nile virus (WNV) is a Flavivirus transmitted by arthropods, and it is a public health concern globally. WNV was originally isolated in Uganda, and within a short period, it spread widely and caused outbreaks worldwide. We conducted this study to analyze strains from Iran, Azerbaijan, the United Arab Emirates, Pakistan, Iraq, and Turkey to understand WNV spread, genetic diversity, and evolution, and to improve monitoring and control programs by evaluating the sources of introduction and modes of transmission. A total of 93 gene sequences from Iran and neighboring countries were downloaded from the NCBI Virus database. After filtering, 89 sequences were used for analysis and the construction of phylogenetic trees for several genes, alongside the genome sequences of reference lineages 1 and 2 for comparison. Sequence alignment was performed in MEGA version 10 via ClustalW. Phylogenetic trees were constructed using the neighbor-joining (NJ) method. Phylogenetic grouping stability was determined via bootstrap analysis (1,000 replications). Our analyses of the *capsid*, *envelope protein*, and *NS5* genes demonstrated the importance of Iran in the circulation of WNV in the region. Although some sequences from Iran cluster with Turkish sequences, others show evidence of independent evolution. The clustering of Azerbaijani sequences with Turkish sequences and the divergence of Iraqi and Pakistani strains revealed varying degrees of connectivity and isolation. Furthermore, the hosts identified in the region include different species of mosquitoes, birds, and mammals, which are described in detail. Our phylogenetic analysis revealed the geographical distribution of WNV transmission. The genetic diversity and connectivity of the strains provide crucial information for epidemic prediction, viral transmission, and areas that require enhanced surveillance. In the future, these evolutionary patterns will also assist in monitoring WNV transmission in Iran and its neighboring countries.

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1. Context

West Nile virus (WNV) is an enveloped, single-stranded, positive-sense RNA virus belonging to the Japanese encephalitis serocomplex, which includes a group of closely related viruses in the genus Flavivirus, family Flaviviridae [1]. This virus is the main cause of the human disease known as West Nile fever, which is an important public health concern in humans and animals. It is considered one of the most widely distributed arthropod-borne viruses [2].

The genome of WNV consists of a single strand of RNA approximately 11 kb in length. The viral RNA encodes ten proteins, which include three structural proteins: C (capsid), prM (premembrane), and E (envelope), as well as seven nonstructural proteins NS1, NS2A, NS2B, NS3, NS4A, NS4B, and NS5. The RNA is translated into a single large polyprotein that is subsequently cleaved by both viral and host proteases into individual proteins. The structural proteins comprise the virion, which encapsulates the viral RNA, and the nonstructural proteins from the replication complex [3].

This virus was first isolated from a febrile patient who lived in the West Nile District of Uganda in 1937. The first cases of WNV infection in horses were recorded in the 1960s in France and Egypt. Since then, the virus has caused recurrent outbreaks in Africa, the Middle East, and parts of Europe. Reported cases of WNV in Turkey occurred during the 1970s and 1990s, as did severe epidemics in 2010-2011. Iran has also reported cases dating back to the 1970s, 2008, and 2009, with patients showing fever and some neurological signs. A study conducted on horses in Iran between 2008 and 2009 revealed widespread WNV spread in the western and southern provinces [4].

WNV has been identified in 65 distinct species of mosquitoes and more than 326 species of birds. The primary vectors for transmission to mammals, including humans, are *Culex* spp. [5]. *Culex pipiens*, *Aedes caspius*, and *Culex theileri* are reported as potential vectors for WNV in Iran [6]. It exists in its natural environment through the enzootic cycle, with *Culex* mosquitoes as vectors and specific species of birds as primary amplifying hosts. While mammals, including humans and horses, can develop WNV infections, they typically do not generate enough viremia to reinfect *Culex* mosquitoes; therefore, they are considered dead-end hosts [7, 8]. Viremia most commonly lasts for a few days, but depending on the host species, viremia intensity varies greatly, and is greater in birds than in mammals [5].

Assessing the actual incidence and prevalence of infections is difficult owing to the differing testing methods available. Nonetheless, whole-blood polymerase chain reaction (PCR) is more sensitive than IgM enzyme-linked immunosorbent assay (ELISA) and requires further investigation as a possible means of diagnosis. In North America, the rapid spread of the WNV prompted veterinary vaccine development by 2005; however, the development of a human vaccine remains in preclinical studies [9].

WNV has at least nine different lineages. Nevertheless, lineages 1a and 2 are the primary causes of most reported human cases [10]. The original lineage 2 strain was dominant in the African, Middle Eastern, Arab, Russian, and European regions for more than 60 years, giving rise primarily to milder infections. Lineage 1, however, emerged in the mid-1990s, causing neurological infections in Europe, Russia, and Israel [9]. Lineage 1 of the WNV can be further divided into three sublineages: 1a, 1b, and 1c. Lineage 1b, also known as Kunjin virus, primarily occurs in Australia. Lineage 1c, also referred to as lineage 5, comprises isolates from India [11]. Lineage 3, also known as the Rabensburg virus, and several other less common lineages, including lineage 4 in Russia, lineage 5 in India, and lineage 6 in Spain, have all likely entered the Northern Hemisphere through separate introductions. Further lineages continue to be discovered in Africa [12].

Phylogenetic analysis employs phylogenetic trees to investigate evolutionary relationships among species or genes. The trees provide researchers with the ability to trace lineages back to a common ancestor and shed light on the evolution of organisms and gene sequences. These relationships are important for the prediction of gene function, tracking disease emergence, and guiding decisions in other areas such as conservation biology and drug development [13]. Recent studies on vector-borne pathogens have emphasized the importance of molecular detection, phylogenetic analysis, and serological surveillance in assessing disease transmission dynamics [14-18].

Recent advancements have enhanced our understanding of WNV, mainly by investigating its genetic, transmission, and environmental factors linked to outbreak initiation. Studies on the genetics of the WNV have revealed interesting patterns in how it spreads and changes in Europe [10, 19]. Recently, a study found the WNV in an area that was previously considered low-risk, which shows how it is spreading unexpectedly. Many people who became infected did not notice mosquito bites or realize they should take precautions [20]. There are also some advancements in understanding host selection of this virus, revealing ecological and environmental determinants influencing its role in

transmission of the WNV [7]. New evidence further shows that, besides ecological determinants conducive to the presence of birds and mosquitoes, land use within agricultural regions can play a pivotal role in the emergence of WNV [21].

While WNV has been documented in Iran since the 1970s, reports of genetic data on Iranian strains in comparison to neighboring countries are still lacking. The concern here lies in the uncertainty over whether Iran serves as a major hub for transmission of the virus or merely acts as a pass-through corridor for the neighboring countries, especially through migratory birds or common ecosystems. This study is the first to report a multi-gene phylogenetic study of WNV strains from Iran and neighboring countries. We have demonstrated regional connections but also distinct evolutionary aspects of WNV strains, which suggest that Iran has been both a recipient of WNV and may represent a potential source of WNV spread in this region. WNV has been frequently reported in Iran, as well as in many bordering countries [22-25]. In this study, we constructed phylogenetic trees using 93 available genome datasets from WNV samples collected in Iran and neighboring countries. This allowed us to trace the evolutionary relationships and diversity of the viruses in the region. By analyzing these trees, we were able to determine the patterns of transmission of this virus and the possible sources of introduction. This information is valuable for revealing the pathways through which the WNV might spread and for developing surveillance and control strategies. Our research will also shed light on the genetic diversity of the virus, providing essential insights for future development of vaccines and therapeutic agents.

2. Data Acquisition

For this study, gene sequences from Iran and bordering countries, including Azerbaijan, Iraq, Pakistan, the United Arab Emirates, and Turkey, were available and initially downloaded from the NCBI Virus database. An initial analysis involving all WNV sequences from these countries was carried out. All WNV sequences from these countries, as submitted to the NCBI Virus database, were selected for evaluation. Each sequence was then analyzed for the presence of the genes encoding the capsid protein, envelope protein, and NS5 protein. All sequences containing these genes were selected. Furthermore, all whole genome sequences were also included in the study. A total of 93 sequences were retrieved. The sequences were distributed as follows: seven from Azerbaijan, 11 from Iran, two from Iraq, four from Pakistan, 68 from Turkey, and one from the United Arab Emirates. Among the 93 sequences analyzed, 89 were used based on the previously stated criteria to construct phylogenetic trees for the complete genome, capsid protein, envelope protein, and NS5 protein. One sequence from Turkey, two from Pakistan, and two from Iran were excluded because of their lack of relevance to these genes. Figure 1 shows the locations of the sequences analyzed in this study. Furthermore, genome sequences from lineages 1 and 2 were included to examine the relationships between these countries and the reference sequences.

Gene sequences in FASTA format were imported into MEGA10, and sequence alignments were performed via ClustalW. Neighbor-joining (NJ) was used to generate phylogenetic trees. The reliability of the phylogenetic groupings was evaluated via a bootstrap test (1,000 replications). The study used NJ and the bootstrap test based on the research of Shah-Hosseini et al. The authors presented a strong framework for NJ and its application to similar research questions, which supports the use of NJ [26]. The NJ method, relying purely on pairwise distances (rather than complex probabilistic models), offers a fast and efficient means of constructing phylogenetic trees. For purposes of phylogeny with datasets that are larger and more complex, it is preferred to use maximum likelihood because of its computational efficiency, although maximum likelihood provides superior accuracy for deep evolutionary analyses. The NJ method's flexibility to variable evolutionary rates helps to make it a practical approach for analysis.

In addition to the detailed phylogenetic analyses, a thorough review of the literature was performed to provide evidence for an understanding of WNV transmission in Iran and neighboring countries. We searched the scientific literature using PubMed, Scopus, and Web of Science databases, drawing data from the last decade to capture as much relevant developments as possible. Keywords such as "West Nile virus," "whole-genome sequencing," "phylogenetic analysis," "arboviruses," "zoonotic transmission," and "migratory bird routes" were used. The articles were selected according to their relevance to the subject areas of molecular epidemiology, vector-host ecology, and phylogeographic patterns. Priority was given to studies that used genomic or phylogenetic approaches. Studies that explored hosts, climate, and local transmission pathways were prioritized. This background of the literature provided insight into the sequence data, as well as the necessary data on the transmission potential of WNV strains, with specific emphasis on Iran and the surrounding countries, where regional patterns of transmission, typical ecosystems, and migratory bird routes offer critical background for understanding virus circulation.

Although the approach taken in this study provides a good representation of the phylogenetic relationships of

Figure 1. Location of WNV strains isolated

Note: Sequences shown in the figure were retrieved from the NCBI Virus database and were utilized in this study. Sequence 1 was isolated from Isfahan, Iran (KJ486150.1). Sequence 2 was isolated from the Sepid River, Iran (MF462262.1). Sequences 3 and 4 were isolated from Lorestan, Iran (MN238669.1, MN238670.1). Sequences 5-9 were isolated from Hormozgan, Iran (MW455339.1, MW455338.1, MW455337.1, MW455336.1, and MW455335.1). Among the sequences analyzed, 67 originated from Turkey, seven from Azerbaijan, three from Pakistan, two from Iraq, and one from the United Arab Emirates.

WNV sequences, it does have limitations. First, the inclusion of available sequences from the NCBI Virus database may introduce some biases because there is a possibility of undercoverage in certain geographic areas due to limited sequencing. Additionally, the removal of certain sequences due to missing genes or incomplete genome data may affect the completeness of the study. These limitations will be addressed to improve the description of the phylogenetic analysis and provide a comprehensive assessment of WNV evolution in the region in future studies. Finally, NJ measures exclusively rely on distance matrices, which offer less accuracy than model-based approaches.

3. Results

3.1. Complete genome sequences

The full-genome nucleotide sequences were established for eight WNV isolates. WNV whole-genome sequences were available from Azerbaijan, the United Arab Emirates, Turkey, and Iran. The analysis of WNV sequences revealed 99% site coverage for Iranian sequences that aligned with lineage 2. Furthermore, the sequences from Turkey and the United Arab Emirates displayed significant similarities to one another and to lineage 1. Additionally, the WNV sequences from Azerbaijan showed high site coverage with these lineages. Figure 2 displays the phylogenetic analysis of complete genomes of WNV from Azerbaijan, the UAE, Turkey, and Iran.

3.2. *Capsid* gene sequences

Twenty-two capsid protein sequences, representing strains from Iran, Turkey, Pakistan, and Iraq, were obtained from the NCBI Virus database. To provide a more representative context in the phylogenetic analysis, reference sequences of lineages 1 and 2 were also selected and aligned. Phylogenetic analysis was performed using sequences of the *capsid* gene. Figure 3 shows the phylogenetic analysis of WNV *capsid* gene sequences from Iran, Turkey, Pakistan, and Iraq.

High site coverage of some branches formed by the clustering of Turkey's sequences and those from Iraq signifies the strong reliability of these evolutionary connections. Additionally, the Iranian sequences showed significant clustering. Lineages 1 (NC_009942.1) and 2 (NC_001563.2) served as outgroups, further confirming the phylogenetic structure. The phylogenetic analysis revealed relevant clustering of the sequences from Iran, implying a common ancestry with some genetic resemblance among the strains of WNV circulating in this area. Interestingly, the Iranian sequences also reveal a genetic relationship with strains from neighboring countries such as Iraq and Turkey. This regional clustering suggests that there may have been a his-

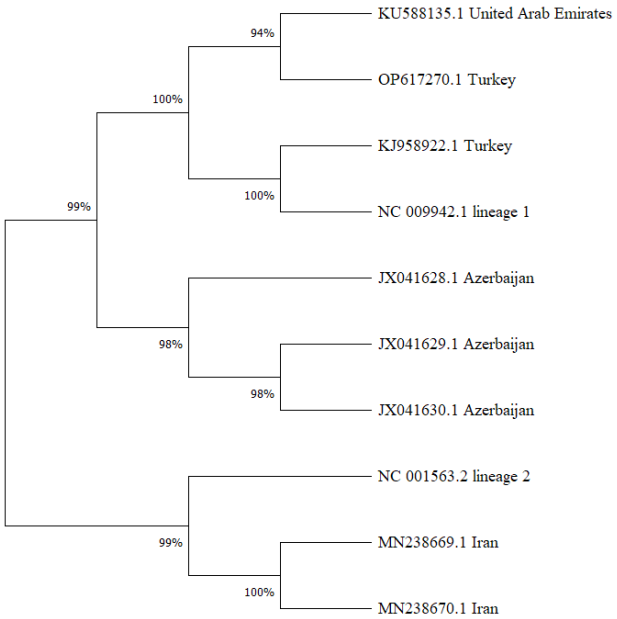

Figure 2. Phylogenetic analysis based on the complete genome sequences of WNV from Azerbaijan, the United Arab Emirates, Turkey, and Iran

Note: The phylogenetic relationships of the full-length sequences were inferred in MEGA10 using the NJ method and tested via 1,000 bootstrap replicates. The sequences are indicated by their GenBank accession number and countries of isolation. The percentages shown in the figure indicate the extent of branch site coverage.

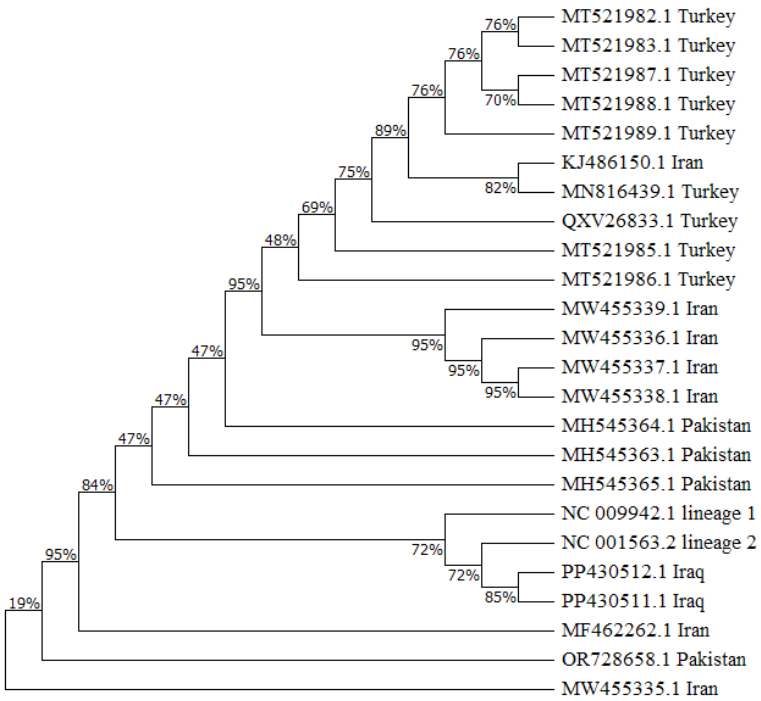

Figure 3. Phylogenetic analysis of the *capsid* gene sequences of WNV from Iran, Turkey, Pakistan, and Iraq

Note: The phylogenetic relationships of the *capsid* gene sequences were inferred in MEGA10 using the NJ method and tested via 1,000 bootstrap replicates. The sequences are indicated by their GenBank accession number and countries of isolation. The percentages shown in the figure indicates the extent of branch site coverage.

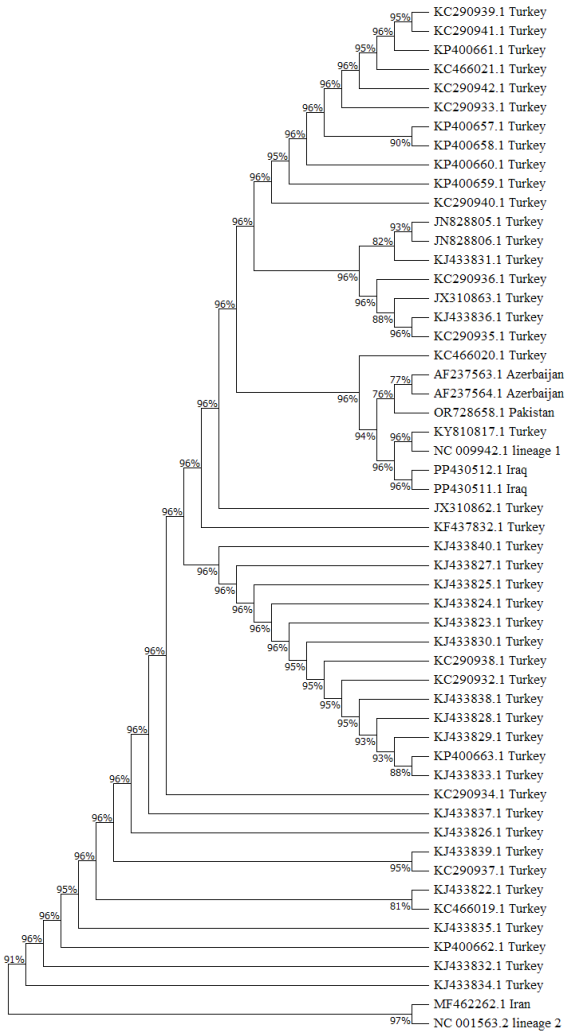

Figure 4. Phylogenetic analysis based on the envelope protein (*E*) gene sequence of WNV from Iran, Turkey, Azerbaijan, and Iraq

Note: The phylogenetic relationships of the *E* gene sequences were inferred in MEGA10 using the NJ method and tested with 1,000 bootstrap replicates. The sequences are indicated by their GenBank accession number and countries of isolation. The percentages shown in the figure indicate the extent of branch site coverage.

torical or ongoing genetic exchange between these countries. This exchange could be driven by migratory birds or by other ecological and environmental factors. The presence of genetic similarities may suggest shared transmission pathways or common environmental conditions that have shaped the evolution of the virus across these areas. Conversely, the Pakistani strains appear to have diverged from the Iranian cluster, forming a separate group. This could signify either a unique evolutionary trajectory in that region or limited genetic exchange between the Pakistani strains and those from Iran.

3.3. The envelope protein (*E*) gene sequences

A total of 54 sequences were included in the analysis, 52 of which originated from Iran, Turkey, Azerbaijan, and Iraq. Additionally, reference sequences for lineage 1 and lineage 2 were included. The majority of the sequences in the tree were from Turkey and formed several separate clusters. This may suggest that Turkey was one of the major sites of virus collection. The sequences from Azerbaijan (AF237563.1, AF237564.1) were closely related to those from Turkey, suggesting a geographic link with Turkey. This may indicate that viruses spread or share evolutionary pressures in this region. Iran has a sequence (MF462262.1) placed further apart from these clusters; however, the lack of data for this gene in Iran may influence the results. The Iraqi and Pakistani sequences (PH430512.1, PP430511.1, OR728658.1) also cluster far apart, possibly reflecting geographic or lineage-specific separation. These findings may be useful for comparison with other sequences to understand the relationships between Turkey and its neighbors

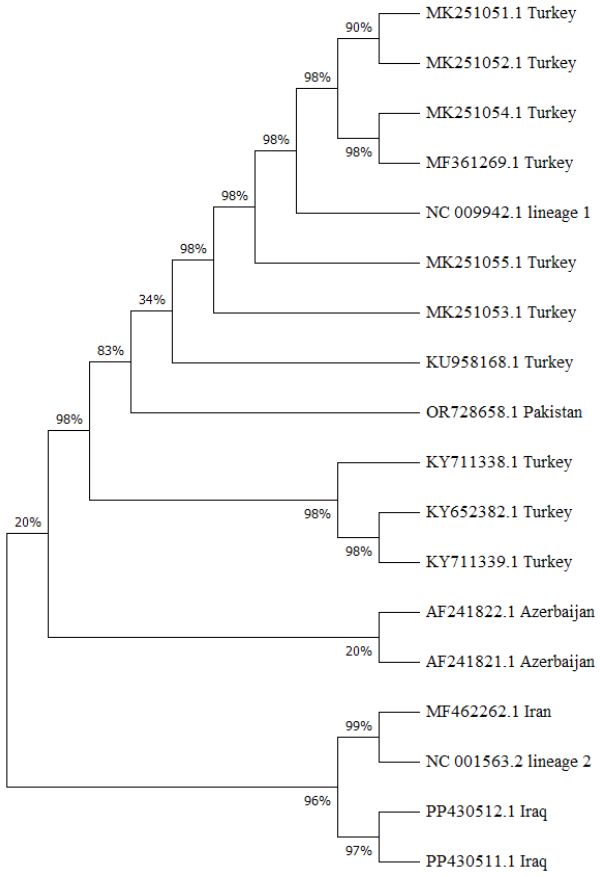

Figure 5. Phylogenetic analysis based on the *NS5* gene sequence of WNV from Turkey, Iran, Azerbaijan, Pakistan, and Iraq

Note: The phylogenetic relationships of the *NS5* sequences were inferred in MEGA10 using the NJ method and tested with 1,000 bootstrap replicates. The sequences are indicated by their GenBank accession number and countries of isolation. The percentages shown in the figure indicate the extent of branch site coverage.

and lineages around the globe. In this dataset, Turkey appears at the center and indeed could act as a hub, given its geographic placement connecting Europe, Asia, and the Middle East. Figure 4 shows the phylogenetic analysis of WNV envelope protein (*E*) gene sequences from Iran, Turkey, Azerbaijan, and Iraq.

3.4. *NS5* gene sequences

The phylogenetic tree was constructed based on 16 *NS5* gene sequences, along with two reference sequences of the WNV. The tree contains samples from Turkey, Iran, Azerbaijan, Pakistan, and Iraq. Some Turkish sequences cluster together, indicating their genetic similarities. Pakistan and Iraq have more distant branches. Considering Iran's central location, the distinct phylogenetic branch could point to virus introductions from eastern regions or neighboring countries such as Pakistan or Iraq, which show evolutionary paths separate from Turkey in the *NS5* phylogenetic analysis. However, the lack of data on the *NS5* gene sequence from Iran may have influenced the findings. A different approach with greater sampling and tracing of biogeographic links could clarify the issues within the analyzed data. The phylogenetic analysis of WNV *NS5* gene sequences from Turkey, Iran, Azerbaijan, Pakistan, and Iraq is depicted in Figure 5.

3.5. Observations across all four trees

Turkish sequences consistently dominate the trees and form multiple distinct clusters. This highlights Turkey as a significant hub of genetic diversity for the WNV. Its geographical location, which links Europe, Asia, and the Middle East, can provide another perspective on filling this role in the evolution of the virus. Iranian sequences often appear in relatively isolated positions or distinct branches. While some Iranian sequences cluster with Turkish sequences, others show signs of independent evolution. Sequences from Azerbaijan tend to group very closely together. Their close association with Turkish sequences indicates strong genetic connectivity, probably resulting from the migratory routes of birds or ecological interactions. Sequences

from Iraq and Pakistan are much more divergent across all trees. The clustering of Azerbaijani sequences together with Turkish sequences and the divergence of Iraqi and Pakistani strains indicates uneven degrees of connectivity and isolation. The inclusion of reference sequences for lineages 1 and 2 in all trees provides a global perspective. Most Turkish and some Azerbaijani and Iranian sequences align more closely to these references, indicating their involvement in globally significant lineages. However, strains from Iraq and Pakistan tend to show greater divergence from these lineages.

3.6. Comparative phylogenetic implications and interpretations

In this study, the analyzed sequences identified hosts of WNV in this region. A total of 32 sequences from Culicidae hosts collected from Iran and Turkey were considered. Twelve sequences were from *Culex*. Among the *Culex* hosts, eight sequences were from *C. pipiens*, whereas the others were from *Culex perexiguus*, *Culex sitiens*, and *C. theileri*. In addition, 27 sequences were associated with human hosts. In Turkey, there were also sequences from *Corvus cornix*, *Ochlerotatus caspius*, *Aedes albopictus*, *Clanga pomarina*, *Equus caballus*, and *Pica pica*. WNV sequence analysis in Iran identified Anatidae and *Anopheles stephensi* as hosts. Anatidae was also identified in Iraq. In the UAE, Camelus was confirmed as a host. Reports from Azerbaijan confirmed *Aedecrobius capensis*, Aves, and *Turdus merula* as hosts. These results provide evidence for the capacity of the virus to cycle through different host species and its ability to cycle through different environments, thereby emphasizing targeted surveillance. A thorough examination of these hosts could enhance our understanding of virus transmission pathways.

How strains of WNV cluster genetically provides useful information about the evolution of the virus and help with outbreak planning. Strains from Pakistan, Iraq, Iran, Turkey, and Azerbaijan exhibit strong genetic relatedness, with the genetic disparity of these strains suggesting that surveillance and response efforts will need to be tailored based on where we are targeting our efforts. Local conditions, including climate, mosquitoes, and the wildlife hosting WNV, provide critical context that determine the spread of WNV in relation to the above factors. These conditions will affect how transmission occurs and how well surveillance and control measures can be implemented. Recognizing the genetic differences can help improve surveillance and prevention measures in the region. Surveillance programmes should consider the genetic groupings when addressing the surveillance and diagnosis of WNV infections. The clustering of Iranian and Turkish strains confirms the possibility of cross-border communication for the monitoring of the virus. Countries that harbor similar WNV strains may benefit from joint surveillance initiatives designed to monitor mutations of the virus and coordinate preventative measures. The degree of divergence of the strains in Iraq and Pakistan suggests local ecological factors that must be taken into account to formulate independent control strategies linking vector control interventions, management, and warning systems. The identification of genetically differentiated strains emphasizes the importance of regionally optimized vector control programs. Indeed, genetic diversity could influence virus-host interactions and, in turn, reduce transmission efficiency and the efficacy of existing mosquito control efforts. Health authorities need to revisit existing strategies to ensure they adequately consider the diversity of circulating WNV strains encountered in different areas.

WNV has been gaining attention as a global health concern. The virus was once restricted to certain areas of the globe but has recently become widespread. Factors contributing to its spread include the migration of infected birds, climate change, and changes in mosquito populations that have allowed transmission within many different ecosystems [8, 20, 27]. The analysis of phylogenetic data is critical for understanding the evolution and spread of WNV. Phylogenetic data reveal genetic relationship patterns of transmission and variation in WNV distributions across different regions and can be used to track outbreaks, understand the origin of WNV, and support public health efforts. This work is especially important in locations where WNV has increased, such as Iran and surrounding countries [21]. This phylogenetic analysis investigated the relationships between WNV transmission patterns in various parts of Iran and neighboring countries. By comparing sequences of the complete genome, capsid, envelope protein, and NS5, we identified several important patterns relevant to epidemiological surveillance. The results provide valuable insight into the linkages between bird and mosquito hosts across countries and WNV evolution.

For several years, WNV has been endemic to the Middle East, with documented outbreaks observed in countries such as Turkey and Iran [28, 29]. In Turkey, the virus has been reported since the 1970s [28]. WNV cases were reported in the 1970s in Iran [29], and there have been many reports of this virus in Iran since then [25]. WNV has also been reported in many other countries surrounding Iran, such as Iraq [30], the United Arab Emirates [23], and Pakistan [24].

The phylogenetic analysis of WNV strains in Iran and neighboring regions shows many similarities with patterns seen in Europe. As described by Simonin et al., birds play a critical role in the dissemination of WNV in both loca-

tions, with their migration found to influence affect patterns of transmission across regions. As in Europe, WNV circulation in Iran is largely ecological, with wetlands serving as the focal point of virus amplification, as these wetland features contain and support populations of mosquitoes and provide the proper ecological space for the virus to amplify. Although WNV strains from Europe demonstrate genetic variation arising from repeated introductions of the virus, along with endemic evolution, strains of WNV in Iran appear to be less genetically diverse than those found in Europe [8]. The results from Iran and neighboring countries are consistent with a recent investigation in Europe showing how temperature, precipitation, and habitat suitability affect viral circulation. Both studies sufficiently demonstrate that bird migration and mosquito vector populations are important determinants of the continuation of WNV transmission cycles. The study by Erazo et al. demonstrated that WNV expansion is also mostly related to climate change [19]. However, limited sequences and analyses in Iran and some neighboring countries restrict this comparison.

In Iran, WNV has many different vectors and hosts that are considered important for the viral transmission cycle. Among mosquitoes, many species, such as *C. pipiens*, *C. theileri*, and *C. perexiguus*, are involved. *C. pipiens* and *A. caspius* are indeed universal transmission vectors. Birds, particularly *Anas sparsa* (Cape teal), are also critical since they can act as reservoirs of the virus in nature and facilitate human transmission. Other mammals, such as humans, pigs, cattle, sheep, and dogs, have been identified as infected hosts [6]. Various hosts in Iran were identified in the sequences analyzed in this study. These included species from the family Culicidae, such as *C. pipiens*, *C. sitiens*, *C. theileri*, and *Culiseta longiareolata*; other hosts included members of the family Anatidae, *A. stephensi*, and *Homo sapiens*. *C. pipiens*, an important vector of the WNV, is the most common mosquito species in some areas of Iran. The presence of *C. pipiens* in these areas greatly increases the probability of transmission of the WNV to humans [6]. In Europe, similar to this study, bird species such as members of the family Anatidae and some vector species, such as *Anopheles* species, have been identified as hosts [31]. Although some avian species, such as Feral Pigeons (*Columba livia domestica*), do not show much evidence of WNV detection, reports from a few studies have revealed that many birds in Iran show positive evidence of WNV circulation [25, 32, 33].

The main mosquito vectors of WNV in Turkey are *C. pipiens*, *Culex quinquefasciatus*, *C. perexiguus*, and *O. caspius*. Other reservoirs of the virus are ducks (*Anas platyrhynchos*), while incidental hosts with high exposure include but are not limited to sheep, horses, and humans [22]. Iran and Turkey share common hosts and vectors for WNV, as shown by phylogenetic analyses. *C. pipiens* is an important mosquito vector in both regions.

C. pipiens and *C. quinquefasciatus* have been identified as the predominant WNV mosquito vectors in the United Arab Emirates [34]. In southern Iraq, both species have also been shown to be WNV vectors [30]. Joseph et al. reported the presence of WNV in dromedary camels in the United Arab Emirates [23]. An analysis of the sequences from this study revealed that *Camelus* species were the hosts in the United Arab Emirates, whereas members of the family Anatidae were the hosts in Iraq. In Pakistan, several *Culex* mosquito species act as significant vectors for WNV [24]. This finding highlights the importance of Culex mosquitoes in the WNV cycle.

In Iran, WNV has been associated with a number of lineages, of which lineage 2 has been the most commonly reported. Phylogenetic analyses revealed that the Russian, Romanian, and Italian WNV strains showed genetic similarity [6]. Lineage 2 was strongly associated with WNV in our phylogenetic trees. The predominant lineages varied among the countries that we studied. In Turkey and Pakistan, lineage 1 is considered a major lineage [22, 24, 35]. Lineage 2 has also been reported in Turkey [36]. Although a study demonstrated the existence of WNV lineage 1 in the UAE, few studies regarding WNV lineages have been conducted there [23]. Iraq and Azerbaijan have also lacked data for particular lineages. Our *NS5* and *capsid* phylogenetic trees indicated that sequences from Iraq clustered with lineage 2. The envelope phylogenetic tree, however, showed some clustering of Iraqi strains with lineage 1 and Turkish strains. The Azerbaijan strains analyzed in our study also showed some associations with lineage 1. This study and previous work strongly emphasize the need for more investigations to determine the geographical impacts of WNV lineages.

WNV likely entered Iran via two migratory bird pathways. First, the virus potentially arrived in central and southern Iran via the East Africa-West Asia Flyway, when it was introduced from Central or East Africa. Second, WNV was likely to have been introduced into northwestern and western Iran from Eastern Europe, such as Romania or Russia, via the Black Sea-Mediterranean Flyway. Genetic analyses suggest that the strains were introduced from separate origins. Although there is evidence of similarities in WNV strains in Iran and neighboring countries, geographical proximity alone is unlikely to play a substantive role in the distribution of the virus. Instead, migratory bird pathways are responsible for WNV epidemiology [6]. Environmental factors, such as proximity to wetlands and climate,

impact WNV transmission. The climate and wetlands of Iran attract migratory birds and create conditions conducive to WNV transmission. Although studies have focused on humans, little work has been conducted to determine the distribution of WNV in avian species in Iran. Given the recent increase in outbreaks in neighboring countries and the intercontinental migratory patterns of birds into Iran, it is important to implement effective control measures [25].

Additionally, Iran's health system should prioritize mosquito control planning and put programs into action, particularly for WNV vectors. WNV surveillance in Iran lacks both mosquito control and diagnostics. WNV vector targeted management should focus on *C. pipiens*, *C. theileri*, and *C. perexiguus*, and be implemented through larviciding, insecticide resistance surveys, and environmental management of stagnant waters. Improved mosquito control will help limit the potential for WNV outbreaks and improve the health of at-risk people. Increasing clinician awareness and implementing WNV-specific diagnostic tests are important in hospitals to increase the detection and care of patients diagnosed with WNV [6]. WNV surveillance of migrating birds, an important transport factor, also needs attention [25]. In addition, our study emphasizes the need to increase sampling in Iran and neighboring countries to better understand host-vector dynamics. Further genome sequencing of mosquitoes and birds may shed light on the genetic variation of WNV and its spread to new regions. Some additional knowledge that may support the understanding of the virus's spread can be gained by identifying the biogeographic links between hosts in Iran and those in neighboring regions. Owing to the important role of hosts in the spread of WNV, we suggest considering other ecological parameters related to interactions among bird species, mosquito vectors, and environmental factors in Iran. Collaboration with neighboring countries will shed more light on the ecological and genetic determinants of WNV transmission. Researchers have suggested that WNV surveillance can be improved in Africa by expanding genomic monitoring in strategic locations, connecting human, animal, and environmental data to better predict when outbreaks will occur, and enhancing global collaboration through international databases. These recommendations aim to mitigate existing surveillance gaps and improve overall preparedness [37]. Another recent study in Europe indicated that by combining indicator-based surveillance (IBS) and event-based surveillance (EBS), researchers can improve risk mapping for WNV. While IBS is based on structured reports of activity from official sources, EBS focuses on outbreak signals from unofficial sources, such as news articles and expert networks. When both sources are integrated with environmental data, the research findings revealed additional areas of concern in Spain, Italy, France, and Greece that were not identified by the traditional approaches [38]. An integrated approach will provide the highest likelihood of controlling WNV disease, especially when mixed, synergistic techniques —such as physical barriers, genetically engineered mosquitoes, and immunological targets —are utilized [39].

The study has some biases that may limit conclusions. Unequal sampling of WNV sequences may over-represent Turkey's genetic diversity and under-represent strains from other countries, such as Iran. In addition, geographical biases introduced by exclusively using sequences from specific locations may miss genetic variation present in regions that were undersampled. Because fewer sequences were sampled from Iran than Turkey, the study may have also underestimated the diversity of strains within Iran and strains connecting Iran with its neighboring regions. Overall, the sampling distribution was unequal for sequences collected across regions. All things considered, sampling across all countries for WNV would more reasonably account for biases, and this expectation of broader sampling may improve phylogenetic studies of viruses, help resolve conclusions, and improve regional surveillance measures moving forward.

4. Conclusion

The phylogenetic analysis revealed the importance of understanding regional dynamics in WNV transmission. The genetic diversity and regional connectivity documented in our study are important sources of information for epidemiological research, helping to predict WNV spread and identify areas that can be monitored and controlled. The analysis of the four phylogenetic trees revealed relationships among WNV strains in the region. Turkey has a central position in the region. Azerbaijan sequences are genetically very close to those of Turkey. The Iranian strains occasionally cluster with the Turkish strains but also occasionally form distinct clusters, suggesting differentiation in their genetic pathways. These results were somewhat constrained by the lack of genome sequences. An expanded study in these areas will shed more light on this topic. These findings indicate an urgent need for more research into the factors driving these patterns.

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Compliance with ethical guidelines

This study did not involve human or animal subjects. The virus gene sequences analyzed were sourced from the Na-

tional Center for Biotechnology Information (NCBI), using publicly available data in accordance with ethical research practices.

Data availability

The sequences of WNV are available in the NCBI Virus Database.

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Authors' contributions

Conceptualization, study design, supervision, review and editing: Hamid Staji; Data acquisition, analysis, interpretation, statistical analysis, writing the original draft, administrative, technical, and material support: Seyedeh Fatemeh Angoshtan.

Conflict of interest

The authors declared no conflict of interest.

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