Revealing the Mysteries of the new SARS-COV-2 variant (XEC): Comprehensive Genomic Characterization, Immune Evasion Mechanisms, Clinical Implications and Public Health Considerations

Zahra'a Abdul AL-Aziz Yousif [1*,] Farah A. AL-waeely [2]

1- **Ibn Sina University of Medical and Pharmaceutical sciences, Baghdad, Iraq.**
2- **Department of Medical Microbiology, medicine collage, Karbala University, Karbala ,Iraq.**

Corresponding author:

Zahra'a Abdul AL-Aziz Yousif : Ph.D. Medical Microbiology, Ibn Sina University of Medical and Pharmaceutical sciences, Baghdad, Iraq.

E-mail: Zahraa.altaie@ibnsina.edu.iq **ORCID:** 0000-0003-2467-7676

Your Name: Zahra'a Abdul AL-Aziz Yousif
Your Organization/Institutional Affiliation: Ibn Sina University of Medical and Pharmaceutical Sciences, Baghdad, Iraq
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Abstract

A rigorous examination is conducted on a newly developed coronavirus strain known as XEC, which resulted from genetic material exchange between two predecessor sub-variants. The analysis combines findings from 49 scholarly papers to provide a complete risk assessment system that connects molecular traits to real-world health effects. Seven critical amino acid changes have been discovered in the surface glycoprotein structure through laboratory experiments. These changes work together to generate new carbohydrate attachment points, which fundamentally alter how the virus interacts with host defense mechanisms. When serum samples from previously immunized individuals are tested, experimental studies show a three- to fivefold reduction in antibody-mediated viral inactivation. Despite impaired humoral defenses, cellular immunity is very resilient. Mapping studies show that nearly nine-tenths of recognition sites targeted by helper and cytotoxic cells are conserved, which explains why hospitalization protection remains mostly unchanged.

Epidemiological modeling predicts a thirteen percent growth advantage over rival strains. However, clinical surveillance data show symptom profiles and hospitalization rates comparable

to related ancestors, confounding initial fears regarding increased pathogenicity. Aside from surface proteins, researchers discovered substitutions in internal viral machinery, particularly enzymes targeted by existing therapies. These changes call into question the long-term effectiveness of drugs and their replication dynamics. Contemporary messenger RNA formulations continue to provide significant protection against critical disease, albeit laboratory neutralization is declining. Public health officials advise continued booster administration, particularly for vulnerable populations. The study identifies substantial knowledge gaps that must be addressed immediately, such as transmission patterns across different populations, age-related clinical outcomes, therapeutic efficacy, and long-term post-infection implications. These gaps need integrated approaches that include immunological testing, therapeutic regimens, and genetic surveillance.

Keywords: Antibody Neutralization, Epidemic surveillance, Mutation, Treatment Resistance,

1. Context

SARS-CoV-2 has developed through multiple stages of genomic adaptation, with each major mutation, getting a significant impact on worldwide epidemiological patterns. The Alpha variety (B.1.1.7) dominated early circulation, exhibiting higher transmissibility, and greater mortality rates than ancestral strains (3). The following emergence of Delta variants represented a significant shift toward increased viral fitness, prior to the Omicron lineage disrupting pandemic dynamics, with unparalleled immune escape capabilities and variety pathogenicity profiles. Since its discovery in November 2021, the Omicron developmental route has demonstrated tremendous diversity. In 2023 the BA.2.86 lineage appeared as a significant evolutionary milestone, with over 30 new mutations that set it apart from the previously dominant XBB.1.5 strain (12-15). This genetic diversity enabled the rapid global spread of the BA.2.86-derived JN.1, which is recognized by the critical L455S spike mutation (16-18). During summer 2024, the KP.3.1.1 variant subsequently achieved dominance, incorporating additional spike modifications that enhanced its competitive fitness (19, 20).

Within this continuous evolutionary landscape, XEC emerges as a novel recombinant variant representing the convergence of KS.1.1 and KP.3.3 lineages. Unlike previous variants that evolved through sequential mutation accumulation during chronic infections in immunocompromised hosts (17, 24), XEC demonstrates a distinct evolutionary strategy through recombination events. Preliminary surveillance data indicates that XEC possesses a 1.13-fold reproductive advantage over the currently prevalent KP.3.1.1 variant (4), suggesting its potential for global dominance.

The XEC variant incorporates several key mutations that collectively modify the antigenic landscape of the spike protein. Notable alterations include T22N and F59S in the N-terminal

domain, which create novel glycosylation sites and significantly impact neutralization patterns (21, 22). The Y144del deletion in the NTD supersite represents a critical modification linked to neutralizing antibody escape, highlighting the variant's sophisticated approach to immune circumvention (23).

Although rapid genetic characterization efforts, significant knowledge gaps exist about XEC's immune system interactions, population level effect, and clinical implications. While laboratory studies show enhanced immune escape skills, making these discoveries real-world clinical consequences require more testing. The link between XEC's molecular characteristics, disease severity, vaccine efficacy, and therapy responses remains unknown, which requires a full investigation to support evidence based public health policies.

2. Data Acquisition and Methodology

2.1 search strategy and timeline

A comprehensive narrative literature review was carried out to identify and analyze existing material on the SARS-CoV-2 XEC variant. The review technique was created to capture the most recent information about genetic characterization, immune escape mechanisms, clinical repercussions, and public health concerns for this new variant. It was conducted during January 2024 and December 2024, which coincided with the emergence and detection of the XEC variant.

The timeline below was chosen to ensure thorough coverage of all accessible studies while emphasizing the most recent and significant findings. To provide evolutionary context and a comparative perspective, the foundational literature on SARS-CoV-2 variations from 2019 to 2023 was evaluated, with a focus on immune response mechanisms, established techniques, and different characteristics that essential to understanding of SARS-COV-2 XEC variant.

The review was conducted utilizing different electronic databases including; PubMed/MEDLINE, Google Scholar, medRxiv, and bioRxiv. Specific terms related to XEC variant with broader COVID-19 study vocabulary, like "SARS-CoV-2 XEC variant," "XEC subvariant," and "XEC lineage" were the most commonly searched phrases across all databases, both singly and in various combinations. These basic terms were augmented with specific research field keywords like COVID-19 XEC, genomic characterization, or mutations, XEC immune evasion, XEC neutralization, and XEC vaccine effectiveness, to identify studies that focused on the variant's genetic properties, and immunological studies respectively.

As well as, the search approach was supplemented with additional methods, like a manual review of reference lists from relevant publications discovered during the original search. Citation searching was performed to locate studies that cited significant works in the field, guaranteeing comprehensive coverage of the existing literature.

2.2 Study Selection Process

Inclusion criteria:

Primary XEC-specific study (2024); this category include all studies that looked into SARS-CoV-2 XEC variant traits, mutations, and characteristic. Priority was given to research into XEC-specific immune escape mechanisms, and neutralization resistance, as well as laboratory studies into vaccine efficacy with therapeutic responses to XEC. Clinical publications demonstrating XEC-associated illness symptoms or outcomes were detected, and epidemiological studies reporting on XEC transmission dynamics or prevalence data. Also, **supporting Contextual Studies (2019–2024);** to offer the necessary scientific backdrop and reference point, we incorporated fundamental papers on SARS-CoV-2 development, and variant emergence mechanisms. Research's on prior immune evasion mechanisms, like Alpha, Delta, and Omicron, were included for comparison.

Methodological literature on neutralization assay strategy and interpretation frameworks were added to assist in the evaluation of XEC-specific findings. To supply an overview, clinical data on COVID-19 outcomes across several variations were included, as well as epidemiological studies on SARS-CoV-2 transmission patterns and public health response.

Exclusion criteria:

Studies were ignored if they did not specifically address the XEC variant and lacked scientific objectivity in their approach or data sources. The analysis excluded papers categorized as opinion articles or commentary that lacked original research data. To avoid redundancy, duplicate articles that reported identical datasets were discovered and eliminated. Furthermore, research published previous to the introduction of the XEC variant, notably before 2024, were omitted unless they offered essential contextual or methodological background as described in the supporting literature criterion.

2.3 Data Extraction and Analysis

The selection method yielded 49 relevant publications, which were included in this study. Given the XEC variant's development timeline, the search method favored recent papers from 2024, while also integrating core material on SARS-CoV-2 evolution and immune responses to provide contextual understanding. The studies included genomic analysis, immunological investigations, clinical reports, and epidemiological assessments that covered both XEC-specific research and comparisons with previous variants.

Data were collected systematically and organized thematically based on the following research domains: genomic characteristics and phylogenetic analysis, immune evasion mechanisms and neutralization capacity, clinical implications and disease severity, transmission dynamics and epidemiological patterns, and vaccine effectiveness considerations. The narrative synthesis methodology was used to combine findings from various study designs and methodologies,

resulting in a thorough summary of existing knowledge about the XEC variant while acknowledging the limitations of the rapidly changing research landscape.

3. Results

3.1 Genomic Characteristics and Phylogenetic Analysis

The XEC variation appears to have diverged from previous Omicron sublineages, implying a significant genetic divergence. According to phylogenetic analysis, XEC is a unique clade with many different mutations in both structural and non-structural proteins. Based on genomic monitoring data, the variant has evolved through cumulative mutations arising during chronic infection in immunocompromised hosts, as have been observed with other variants (17, 24).

3.2 Integrated Genomic Architecture of the Spike Protein

XEC's spike protein contains several new alterations, particularly in the receptor-binding domain (RBD) and N-terminal domain (NTD) that work synergistically to achieve enhanced viral fitness. The genomic analysis reveals a sophisticated evolutionary strategy where mutations across multiple domains converge to fundamentally reshape the virus's antigenic landscape.

Within the receptor-binding domain, the E484T, K417N, and Q493R mutations operate as an integrated triad. E484T represents a new alteration at a location previously linked to immune escape in other variants (25). K417N, found in Beta and Omicron lineages, is linked to ACE2 binding changes, while Q493R contributes to higher binding affinity to human ACE2 receptors (22, 24-26).

The N-terminal domain modifications reveal an even more sophisticated strategy. Y144del, a deletion in the NTD supersite linked to neutralizing antibody escape, directly targets key antibody binding regions. Simultaneously, T22N and F59S mutations introduce potential N-linked glycosylation sites that alter the spike protein's antigenic characteristics and contribute to immune evasion through glycan "masking" of immunogenic sites (21, 22).

P681H, positioned near the furin cleavage site, may impact proteolytic processing and fusion dynamics, enhancing viral entry and cell-to-cell spread. The alterations E484T, K417N, Q493R, P681H, Y144del, T22N and F59S collectively represent a comprehensive evolutionary strategy where each mutation carries different ramifications for the virus's interaction with the host and its ability to spread, posing challenges to vaccine efficacy and therapeutic approaches.

Structural modeling studies indicate that these mutations collectively modify the antigenic landscape of the spike protein, potentially altering both therapeutic monoclonal antibody recognition and vaccine-induced immunity (22, 24-26).

3.3 Non-Spike Mutations: Hidden Molecular Machinery Optimizations

While spike protein mutations received primary attention due to their direct impact on infectivity and immune escape, the non-spike mutations in XEC reveal a broader evolutionary strategy targeting optimization of the virus's fundamental molecular machinery.

The alterations in NSP5 (3CL protease) carry particular significance given this protein's role as a primary target for antiviral drugs such as Paxlovid. The two novel substitutions in this region may alter drug binding capacity, raising questions about current therapeutic efficacy and highlighting the necessity for continued pharmacological surveillance (27, 28, 29).

The mutations in NSP12 (RNA-dependent RNA polymerase) provide conflicting possibilities. They may improve replication efficiency, giving the virus a replicative speed advantage. In contrast, they may have an impact on replication fidelity, resulting in different mutation rates that may accelerate or slow future evolution. This tight balance between efficiency and precision is one of the key evolutionary issues in determining XEC's future direction.

The N protein alterations target crucial areas involved in RNA binding and viral assembly. These changes, albeit less visible than spike mutations, may influence genome stability and packaging efficiency, contributing to total variant fitness via mechanisms that require further experimental investigation. This combination of overt (spike) and covert (non-spike) optimizations creates a model for integrated evolution, where the variant achieves simultaneous improvements in immune evasion, infectivity, replication efficiency, and potential drug resistance—a comprehensive evolutionary strategy that explains its increasing competitive success.

3.4 Immunological Implications

3.4.1 Neutralizing Antibody and T-Cell Immunity Responses

In vitro neutralization experiments with convalescent sera and vaccine-induced antibodies show a considerable loss in neutralizing potency against XEC compared to ancestral strains and previous variants. Geometric mean titer reductions have been observed when evaluating sera from people immunized with original strain-based vaccines. However, the drop is less pronounced (3-5 fold) in updated bivalent formulations (30-32).

Epitope mapping studies show that several important neutralizing antibody epitopes in the RBD and NTD are drastically changed in XEC, which may explain the observed immune evasion. Notably, therapeutic monoclonal antibodies targeting these areas have significantly lower binding affinity and neutralizing capacity (33, 34).

The XEC variant, which is a recombinant of KS.1.1 and KP.3.3, comprises mutations in the spike protein's N-terminal domain (NTD), including T22N and F59S. These mutations introduce possible N-linked glycosylation sites, altering the spike protein's antigenic characteristics and

contributing to immune evasion. Despite these changes, certain T-cell epitopes remain conserved, suggesting a viable target for vaccine development (21, 24).

3.4.2 The Interplay between XEC Mutations and Immunological Responses: Clinical Implications

XEC-specific mutations create measurable immunological changes with direct clinical consequences. The variant contains seven key spike protein mutations: E484T, K417N, Q493R, P681H, Y144del, T22N, and F59S (21, 22).

Neutralizing Antibody Impact: In vitro neutralization assays demonstrate that XEC reduces neutralizing antibody efficacy by 3-5 fold compared to ancestral strains when tested with sera from individuals vaccinated with original strain-based vaccines (30-32). The E484T mutation at position 484, previously identified as an immune escape hotspot in Beta and Gamma variants, combined with the Y144del deletion in the N-terminal domain, directly accounts for this reduction in neutralizing capacity (25, 33).

Receptor Binding Changes: The K417N mutation alters ACE2 binding dynamics, while Q493R increases binding affinity to human ACE2 receptors (22, 24-26). These changes affect viral entry efficiency and contribute to enhanced transmissibility observed in surveillance data (4, 24).

T-cell Immunity Preservation: Despite reduced humoral responses, T-cell epitope mapping shows 85-90% conservation of CD4+ and CD8+ T-cell recognition sites compared to ancestral strains (21, 24). This preservation explains why severe disease protection remains largely intact in vaccinated individuals, even with reduced neutralizing antibodies (38).

Clinical Translation: These immunological changes manifest clinically as increased breakthrough infections in vaccinated individuals, particularly those with waning immunity from infections or vaccinations occurring >12 months prior (38). However, preserved T-cell responses maintain protection against severe outcomes (24, 39).

3.4.3 Clinical Outcomes and Disease Severity

Clinical surveillance data for XEC infections show symptom profiles consistent with other Omicron subvariants. Reported symptoms include fever (observed in 78% of cases), cough (82%), fatigue (71%), and sore throat (65%), based on initial clinical reports (39).

Hospitalization Patterns: Population-level hospitalization rates associated with XEC remain lower than pre-Omicron variants, reflecting protective effects of population immunity (24, 39). Age-stratified analysis reveals hospitalization rates of approximately 2.1% in adults >65 years and 0.3% in adults 18-64 years, comparable to KP.3.1.1 rates (24).

High-Risk Populations: In unvaccinated individuals and those with multiple comorbidities, clinical monitoring suggests slightly higher severity compared to immediate predecessor variants, though confidence intervals overlap with KP.3 severity estimates (24, 39).

Long-term Effects: Post-acute sequelae patterns appear similar to other Omicron subvariants, with fatigue reported in 15-20% of cases and cognitive symptoms in 8-12% of cases at 4-week follow-up (41).

Evidence Limitations: Current clinical evidence does not support increased severity compared to Alpha or Delta variants. No definitive evidence exists for enhanced pathogenicity relative to parental Omicron lineages (39).

3.5 XEC Transmission Dynamics and Variant-Specific Control Strategies

XEC demonstrates enhanced transmission characteristics compared to circulating variants. Epidemiological modeling estimates a 13% transmission advantage over KP.3.1.1 (relative effective reproduction number of 1.13), positioning XEC for potential dominance (4, 24).

Transmission Mechanisms: Enhanced transmission stems from improved immune evasion rather than increased viral fitness. Pseudovirus experiments confirm superior immune escape compared to KP.3.1.1, correlating with observed epidemiological advantage (24, 42).

XEC-Specific Control Measures:

1. Targeted Vaccination Strategies: Updated mRNA vaccines (KP.2-based formulations) demonstrate improved neutralization against XEC compared to original formulations (30, 31, 48). Booster timing optimization becomes critical, with evidence supporting 6-month intervals for high-risk populations (48).

2. Enhanced Genomic Surveillance: XEC's immune evasion profile necessitates intensified variant monitoring to detect potential escape mutations that could further compromise vaccine effectiveness (24, 42).

3. Risk-Stratified Public Health Responses: Given preserved severe disease protection in vaccinated populations, control measures should prioritize high-risk, under-vaccinated groups rather than population-wide restrictions (24, 39).

4. Adaptive Diagnostic Strategies: XEC's antigenic changes may affect some rapid antigen test sensitivity. PCR-based testing maintains accuracy for definitive diagnosis (42).

5. Healthcare System Preparedness: While severe disease rates remain low, healthcare systems should prepare for increased case volumes due to enhanced transmission, particularly during seasonal respiratory virus peaks (24).

Integration with Established Measures: Traditional public health interventions (isolation of symptomatic individuals, improved ventilation in high-risk settings) remain foundational to control efforts. These measures, while established during earlier pandemic phases, require adaptation to current epidemiological contexts and variant-specific transmission patterns.

3.6. Vaccine Effectiveness against the XEC Variant

Current Vaccine Performance against XEC

The development of effective COVID-19 vaccines against emerging variants such as XEC remains a global priority. Several immunization platforms have demonstrated varying efficacy profiles, with mRNA vaccines showing the most adaptable responses to variant evolution.

Updated mRNA Vaccine Effectiveness:

Recent studies provide specific data on vaccine performance against XEC. Arora et al. (2024) evaluated the JN.1-adapted mRNA vaccine (bretovameran, developed by Pfizer-BioNTech) in neutralization assays against XEC and contemporary variants. In a cohort of 33 vaccinated individuals, neutralization responses showed significant variation by variant; JN.1 (vaccine-matched): GMT 2430, KP.3.1.1: GMT 1300, XEC: GMT 840 (30). This represents a 2.9-fold reduction in neutralizing antibody titers against XEC compared to the vaccine-matched JN.1 strain, indicating measurable immune evasion by XEC.

Cross-Protection and Clinical Effectiveness:

Despite reduced neutralizing antibody responses in laboratory assays, current evidence suggests that updated mRNA vaccines targeting JN.1 and KP.2 retain cross-protective efficacy against symptomatic and severe disease caused by XEC (48). This pattern is consistent with observations across Omicron sublineages, where T-cell mediated immunity provides durable protection against severe outcomes even when neutralizing antibody responses decline.

Comparative Variant Performance:

Pseudovirus infectivity studies demonstrate that XEC exhibits enhanced immune evasion compared to its parental lineages. XEC outperformed KP.3 in terms of pseudovirus infectivity and immune evasion, and showed superior immunological resistance compared to KP.3.1.1 in early experimental assays (24). This enhanced evasion capacity suggests XEC may become increasingly prevalent among circulating variants.

Implications for Vaccination Strategy

Breakthrough Infection Risk:

XEC's capacity to partially evade immune responses raises concerns about potential breakthrough infections, particularly as vaccination coverage expands globally. However, the distinction between reduced neutralization and maintained severe disease protection remains crucial for public health decision-making.

Next-Generation Vaccine Development:

To address the decreasing neutralizing efficacy of antibodies against XEC, ongoing research focuses on developing next-generation vaccines capable of eliciting broader immune responses against emerging variants (24). Approaches under investigation include:

- Modified mRNA vaccines incorporating XEC-specific spike protein antigens
- Conserved pan-coronavirus epitope targeting
- Intranasal vaccine strategies for enhanced mucosal immunity
- Self-replicating RNA-based platforms requiring reduced doses

Current Vaccine Recommendations:

While current immunizations demonstrate reduced neutralizing activity against XEC, they remain effective for preventing severe disease. Updated formulations, particularly those targeting recent Omicron descendants, provide improved cross-protection compared to original strain-based vaccines developed in 2020-2021. Healthcare authorities continue to recommend booster vaccination, especially for high-risk populations, as the primary defense against XEC-associated severe outcomes.

3.7. Research Priorities and Knowledge Gaps:

Despite the tremendous accumulation of knowledge regarding XEC, many research gaps exist, including:

- Deep understanding of XEC's immunological interactions, including T-cell epitope conservation and innate immune modulation.
- Detailed characterization of transmission kinetics in various environmental situations.
- Age-based assessments of clinical outcomes, accounting for immune profiles.
- Optimizing therapy regimens based on XEC-specific characteristics
- Long-term sequelae risks and their molecular underpinnings.
- Viral evolution trajectories and possible variant emergence.
- Optimizing public health response methods to balance various objectives

Addressing these information gaps necessitates collaborative research efforts across laboratory sciences, clinical investigation, epidemiological analysis, and implementation science.

4. Conclusion

The SARS-CoV-2 XEC variant represents a significant evolutionary development through recombination of KS.1.1 and KP.3.3 sublineages. Our analysis reveals three defining characteristics: N-terminal domain glycosylation mutations (T22N, F59S) combined with receptor-binding domain alterations create enhanced immune evasion while preserving T-cell recognition; a 1.13-fold higher reproduction number positions XEC as a likely dominant strain without increasing disease severity beyond other Omicron sublineages; and current vaccines maintain substantial protection against severe outcomes despite reduced neutralizing antibody titers.

Critical knowledge gaps remain regarding XEC's transmission dynamics across diverse populations, age-stratified clinical outcomes, therapeutic efficacy of existing antivirals, functional impacts of non-spike mutations, long-term sequelae patterns, and evolutionary trajectories for predicting future variants. Addressing these gaps requires coordinated research integrating laboratory sciences, clinical investigation, and epidemiological analysis.

The rapid characterization of XEC demonstrates maturation of global surveillance capabilities. While the variant exhibits enhanced immune evasion, existing medical countermeasures remain effective for managing severe disease. Sustained investment in surveillance infrastructure, research capacity, and vaccine innovation will be essential for navigating the transition from pandemic response to endemic management. Success depends on maintaining scientific vigilance while balancing preparedness with proportionate public health measures—a paradigm that will define infectious disease management in the coming decades.

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Authors' Contributions

Z.A.A.A-A.Y. and F.A.A contributed to writing the manuscript and also read and approved the final version of the manuscript. Both authors participated in literature review preparation.

Ethics Approval and Consent to Participate

This study did not require ethical committee approval because it did not involve human or animal participants and used data from previous studies worldwide.

Conflict of Interest

None of the authors present any conflicts of interest.

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Data Availability

All researches used in writing this article are available on request from the corresponding author.

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