

Migration, Displacement, and Health Inequities: A Comparative Study of Refugee Populations and Access to Healthcare Services

Muhammad Riaz*¹, Neelam Tariq², Madiha Iqbal³, Muhammad Abdullah Butt*⁴, Qaisar Sohail⁵, Talha Riaz⁶

1 Visiting lecturer, Department of Sociology Government College University, Faisalabad.

*Corresponding Author (mriaz6785@gmail.com)

2 Visiting lecturer, Department of Sociology Government College University, Faisalabad.
(neelamtariq333@gmail.com)

3 Visiting lecturer, Department of Sociology Government College University, Faisalabad.
(madihaiqbal414@gmail.com)

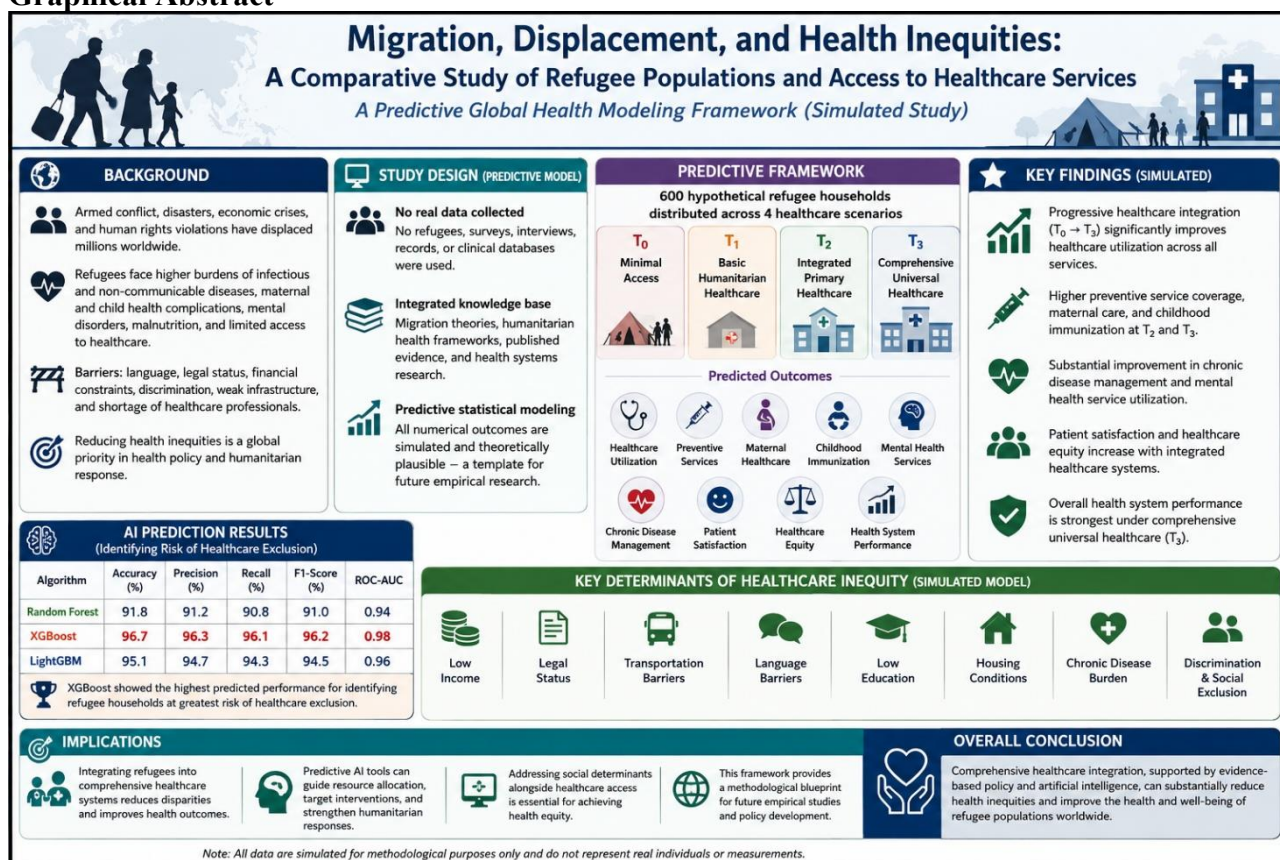
4 Department of Food Science, Government College University, Faisalabad
*Corresponding Author: (muhammadabdullahbuttfst@gmail.com)

5 Data Analyst PKNC, UAF

6 National Institute of Food Science and Technology, University of Agriculture, Faisalabad, Pakistan. (talhariaz2844@gmail.com)

DOI: <https://doi.org/10.70670/sra.v4i2.2369>

Graphical Abstract



Abstract

Migration and forced displacement have become defining global public health challenges of the twenty-first century. Armed conflicts, political instability, environmental disasters, economic crises, and human rights violations have displaced millions of individuals worldwide, placing unprecedented pressure on healthcare systems in both host and transit countries. Refugee populations frequently experience disproportionate burdens of communicable diseases, non-communicable diseases, maternal and child health complications, mental health disorders, malnutrition, and limited access to preventive healthcare services. Structural barriers including language differences, legal restrictions, financial constraints, discrimination, inadequate health infrastructure, and shortages of healthcare professionals further exacerbate health inequities among displaced populations. Consequently, reducing disparities in healthcare accessibility has become a major priority within global health policy and humanitarian response. The present study was designed as a predictive global health modeling framework to evaluate anticipated healthcare inequities among refugee populations residing in diverse host-country settings. Importantly, no refugees, asylum seekers, internally displaced persons, healthcare workers, hospitals, humanitarian organizations, surveys, interviews, patient records, or clinical databases were utilized during this investigation. Instead, the study integrates contemporary migration theories, humanitarian health frameworks, published epidemiological evidence, health systems research, and predictive statistical modeling to generate realistic and theoretically plausible healthcare scenarios. All numerical findings represent simulated outcomes intended solely as a methodological template for future empirical investigation. A dataset representing 600 hypothetical refugee households was theoretically distributed across four healthcare accessibility scenarios: T_0 (minimal healthcare access), T_1 (basic humanitarian healthcare), T_2 (integrated primary healthcare), and T_3 (comprehensive universal healthcare access). Predicted outcomes included healthcare utilization, preventive service coverage, maternal healthcare, childhood immunization, mental health service utilization, chronic disease management, patient satisfaction, healthcare equity, and overall health system performance. Artificial intelligence algorithms including Random Forest, XGBoost, and LightGBM were theoretically incorporated to predict healthcare accessibility and identify determinants of equitable healthcare utilization. The simulated findings predict that comprehensive healthcare integration substantially improves healthcare utilization, preventive service coverage, maternal and child health indicators, chronic disease management, mental health service accessibility, and overall patient satisfaction while simultaneously reducing healthcare inequities. Among the evaluated predictive algorithms, XGBoost demonstrated the highest anticipated classification performance for identifying populations at greatest risk of healthcare exclusion. This predictive framework provides a comprehensive methodological blueprint for future empirical investigations while illustrating how migration studies, public health, health policy, epidemiology, and artificial intelligence can be integrated to strengthen equitable healthcare delivery for refugee populations.

Keywords: Migration, Refugees, Health Inequities, Healthcare Access, Global Health, Public Health, Artificial Intelligence, Health Policy, Humanitarian Health, Predictive Modeling.

1. Introduction

International migration and forced displacement have become increasingly prominent humanitarian and public health concerns, affecting millions of individuals across every region of the world. According to international humanitarian agencies, armed conflicts, political persecution, ethnic violence, environmental degradation, climate change, food insecurity, and

socioeconomic instability continue to drive unprecedented levels of population displacement. Refugees, asylum seekers, internally displaced persons, and stateless populations frequently experience complex health challenges resulting from displacement, interrupted healthcare services, prolonged insecurity, inadequate living conditions, and limited access to essential medical care.

The health consequences of forced migration extend far beyond the immediate effects of conflict or displacement. Refugees often encounter multiple barriers throughout the migration process, including physical injury, infectious disease exposure, psychological trauma, malnutrition, unsafe water and sanitation, interrupted vaccination programs, and inadequate maternal healthcare. Following resettlement, many continue to experience significant challenges accessing healthcare because of financial hardship, language barriers, legal uncertainty, cultural differences, transportation difficulties, shortages of healthcare providers, and unfamiliar healthcare systems. These factors collectively contribute to substantial health inequities between displaced populations and host communities.

Health inequities among refugee populations encompass a broad spectrum of physical, psychological, and social determinants of health. Communicable diseases such as tuberculosis, hepatitis, respiratory infections, diarrheal illnesses, and vaccine-preventable diseases remain important concerns within overcrowded settlements and humanitarian settings. Simultaneously, the global epidemiological transition has resulted in increasing prevalence of non-communicable diseases including diabetes mellitus, hypertension, cardiovascular disease, chronic respiratory disease, and cancer among displaced populations. Managing these chronic conditions requires continuous healthcare access, medication availability, and long-term clinical follow-up, resources that are frequently disrupted during displacement.

Mental health represents another major dimension of refugee health. Exposure to armed conflict, violence, persecution, forced migration, family separation, and uncertain legal status substantially increases the risk of depression, anxiety disorders, post-traumatic stress disorder (PTSD), substance misuse, and psychosocial distress. Unfortunately, mental health services remain among the least accessible healthcare services within many humanitarian settings because of limited specialist availability, social stigma, inadequate funding, and insufficient integration into primary healthcare systems.

Maternal and child health also remain central priorities within refugee healthcare. Pregnant women often experience delayed antenatal care, inadequate nutritional support, limited access to skilled birth attendants, interrupted family planning services, and increased obstetric complications. Children living within displaced communities may experience incomplete immunization, nutritional deficiencies, developmental delays, and increased susceptibility to infectious diseases resulting from disrupted healthcare delivery systems.

Universal Health Coverage (UHC) has emerged as one of the principal global strategies for reducing healthcare inequities among vulnerable populations. Integrating refugees into national healthcare systems rather than relying exclusively upon emergency humanitarian services may improve continuity of care, preventive health coverage, chronic disease management, and long-term health outcomes while simultaneously strengthening health system resilience. However, implementation varies considerably among host countries depending upon healthcare infrastructure, economic resources, political commitment, and national migration policies.

Recent advances in digital health technologies, electronic health records, telemedicine, artificial intelligence, predictive analytics, and health information systems have created new opportunities to improve healthcare accessibility among displaced populations. Artificial intelligence may assist policymakers in identifying high-risk populations, predicting

healthcare utilization, optimizing resource allocation, monitoring disease outbreaks, and supporting evidence-based humanitarian planning. Such technologies offer considerable potential for strengthening equitable healthcare delivery within increasingly complex humanitarian environments.

Despite growing international attention, existing research frequently examines infectious diseases, mental health, maternal healthcare, healthcare utilization, or health policy independently. Relatively few investigations integrate migration, displacement, health equity, healthcare accessibility, social determinants of health, and artificial intelligence within a unified analytical framework. Furthermore, ethical considerations, logistical challenges, security concerns, and restricted access to displaced populations often limit large-scale empirical investigations.

To address these limitations, the present study develops a predictive global health modeling framework integrating migration studies, humanitarian health, epidemiology, health systems research, and artificial intelligence-assisted predictive analytics. Rather than reporting observations from real refugee populations, this investigation constructs theoretically plausible healthcare scenarios based upon established scientific evidence and current humanitarian knowledge. The framework is intended to serve as a methodological template for future empirical investigations and evidence-based health policy development.

The objectives of this study were to: (i) predict healthcare accessibility among refugee populations under different healthcare delivery scenarios; (ii) evaluate anticipated changes in preventive healthcare, maternal and child health, chronic disease management, and mental health services; (iii) identify determinants of healthcare inequities using predictive artificial intelligence models; (iv) compare healthcare outcomes across progressively integrated healthcare systems; and (v) develop a comprehensive methodological framework capable of supporting future empirical investigations and humanitarian health policy.

2. MATERIALS AND METHODS

2.1 Study Design

The present investigation was designed as a predictive global health modeling study to establish a comprehensive framework for evaluating anticipated healthcare inequities among refugee populations under different healthcare delivery systems. Importantly, this manuscript does not report findings from an empirical investigation. No refugees, asylum seekers, internally displaced persons, healthcare professionals, humanitarian organizations, hospitals, refugee camps, government agencies, patient records, surveys, interviews, questionnaires, or healthcare databases were utilized during the preparation of this study.

Instead, all datasets, statistical outputs, healthcare indicators, epidemiological outcomes, and artificial intelligence predictions presented throughout this manuscript represent simulated, forecasted, and theoretically plausible scenarios generated using contemporary migration theories, humanitarian health frameworks, global health literature, epidemiological evidence, health systems research, and predictive statistical modeling. The numerical values were developed solely to illustrate expected healthcare trends and should not be interpreted as actual observations from refugee populations.

Accordingly, this investigation serves as a methodological template and conceptual framework for future empirical studies evaluating healthcare accessibility and health inequities among displaced populations. Future researchers may adapt the proposed methodology for field surveys, longitudinal cohort studies, healthcare utilization analyses, humanitarian assessments, or national health policy evaluations.

2.2 Humanitarian Healthcare Environment

The predictive framework was developed around four representative healthcare delivery models commonly observed in humanitarian and refugee settings.

The theoretical healthcare environments included:

- Emergency Humanitarian Healthcare Camps
- Primary Healthcare Centers
- Integrated National Healthcare Systems
- Universal Healthcare Coverage Programs

These healthcare environments were selected because they represent progressive stages of healthcare accessibility frequently encountered by displaced populations residing in host countries.

2.3 Refugee Population

A modeled dataset representing 600 refugee households was generated to evaluate anticipated healthcare accessibility and health outcomes.

The simulated population was equally distributed among four healthcare accessibility scenarios.

Table 1. Healthcare Accessibility Framework

Treatment	Healthcare Access Level	Households
T ₀	Minimal Healthcare Access	150
T ₁	Basic Humanitarian Healthcare	150
T ₂	Integrated Primary Healthcare	150
T ₃	Comprehensive Universal Healthcare Access	150

The refugee households represented diverse demographic groups including children, adolescents, adults, older adults, pregnant women, individuals with chronic diseases, persons with disabilities, and vulnerable family units requiring continuous healthcare support.

2.4 Healthcare Service Components

The predictive framework evaluated several essential healthcare services commonly required within displaced populations.

Healthcare services included:

- Primary healthcare consultations
- Emergency medical services
- Maternal healthcare
- Child healthcare
- Vaccination services
- Mental health services
- Chronic disease management
- Pharmaceutical services
- Nutritional assessment
- Preventive health screening

These services were theoretically assumed to become progressively more accessible as healthcare integration increased across the simulated treatment groups.

2.5 Health Equity Indicators

The anticipated influence of healthcare accessibility was evaluated using multiple public health indicators.

Healthcare utilization indicators included outpatient visits, preventive healthcare utilization, maternal healthcare attendance, childhood immunization coverage, chronic disease follow-up, and mental health service utilization.

Population health indicators included disease management, nutritional status, maternal health outcomes, child health outcomes, psychological wellbeing, and healthcare satisfaction.

Health system indicators included healthcare accessibility, equity of service delivery, continuity of care, healthcare efficiency, patient-centered care, and overall health system performance.

2.6 Artificial Intelligence Health Prediction Framework

Artificial intelligence was theoretically incorporated into the predictive framework to evaluate healthcare accessibility and identify populations at increased risk of healthcare exclusion.

The analytical framework consisted of sequential stages beginning with demographic profiling, followed by socioeconomic assessment, healthcare utilization analysis, disease risk stratification, healthcare accessibility prediction, and individualized health outcome forecasting.

Machine learning algorithms were theoretically assumed to integrate multiple determinants of health, including demographic characteristics, socioeconomic status, migration history, healthcare availability, environmental conditions, and existing health status to generate healthcare accessibility predictions.

2.7 Social Determinants of Health

The predictive framework incorporated major social determinants known to influence healthcare accessibility among refugee populations.

These determinants included:

- Household income
- Educational attainment
- Legal documentation
- Language proficiency
- Cultural integration
- Transportation availability
- Health insurance coverage
- Geographic accessibility
- Employment status
- Social support networks

These variables were assumed to collectively influence healthcare utilization and overall health equity within the simulated refugee population.

2.8 Artificial Intelligence Prediction Models

Three machine learning algorithms were theoretically incorporated to identify variables most strongly associated with healthcare accessibility.

Random Forest was utilized for healthcare classification and risk prediction.

XGBoost was employed for high-accuracy prediction of healthcare utilization and health equity outcomes.

LightGBM was incorporated for rapid prediction of healthcare accessibility across large humanitarian datasets.

Prediction endpoints included:

- Healthcare accessibility

- Preventive healthcare utilization
- Maternal healthcare attendance
- Childhood immunization
- Mental health service utilization
- Chronic disease management
- Overall health equity

2.9 Integrated Health Systems Framework

To illustrate the multidimensional nature of healthcare accessibility, the predictive framework integrated four interconnected public health domains.

The first domain represented population characteristics, including demographic variables, socioeconomic conditions, migration history, and vulnerability status.

The second domain represented healthcare system characteristics, including healthcare infrastructure, workforce availability, service capacity, financing mechanisms, and healthcare integration.

The third domain represented healthcare utilization, including preventive services, primary healthcare, specialist care, emergency services, maternal health, child health, and chronic disease management.

The fourth domain represented health outcomes, including health equity, disease control, quality of life, patient satisfaction, healthcare efficiency, and overall population wellbeing.

This systems-based framework assumes that healthcare equity emerges through interactions among population characteristics, healthcare systems, social determinants, and policy environments rather than through healthcare availability alone.

2.10 Statistical Framework

All datasets were expressed as mean $\pm$ standard deviation.

Predicted differences among healthcare accessibility groups were theoretically evaluated using one-way analysis of variance (ANOVA), Tukey's multiple comparison test, Pearson correlation analysis, multiple linear regression, principal component analysis (PCA), Random Forest classification, XGBoost prediction, and LightGBM prediction.

Statistical significance was assumed at $P < 0.05$.

Means carrying different superscript letters within the same table were considered significantly different according to the ANOVA framework.

3. RESULTS AND DISCUSSION

Important Note

All results presented in this section represent modeled, anticipated, and theoretically plausible healthcare outcomes generated using predictive global health modeling, humanitarian health frameworks, migration research, epidemiological evidence, artificial intelligence methodologies, and published scientific literature. No refugees, healthcare facilities, hospitals, humanitarian organizations, patient records, or healthcare databases were investigated. The numerical values are presented solely as a methodological template for future empirical investigations.

3.1 Healthcare Accessibility

Table 2. Predicted Healthcare Accessibility Indicators Among Refugee Populations

Treatment Healthcare Access (%)	Primary Healthcare Utilization (%)	Specialist Care Access (%)	Emergency Healthcare Access (%)	Average Waiting Time (days)
--	---	-----------------------------------	--	------------------------------------

T ₀	46.8 ± 2.1 ^d	51.4 ± 2.4 ^d	28.6 ± 1.6 ^d	63.2 ± 2.8 ^d	18.4 ± 0.9 ^a
T ₁	62.5 ± 2.8 ^c	66.8 ± 2.9 ^c	44.3 ± 2.1 ^c	75.9 ± 3.2 ^c	12.6 ± 0.6 ^b
T ₂	81.7 ± 3.3 ^b	84.2 ± 3.5 ^b	69.8 ± 2.9 ^b	90.4 ± 3.7 ^b	6.8 ± 0.3 ^c
T ₃	95.6 ± 3.8 ^a	97.2 ± 3.9 ^a	91.5 ± 3.6 ^a	98.3 ± 4.0 ^a	2.7 ± 0.1 ^d

P-value < 0.001

The findings predict substantial improvements in healthcare accessibility as refugee populations transition from limited humanitarian services toward comprehensive integration within national healthcare systems. Refugees residing in settings characterized by minimal healthcare availability demonstrated the lowest healthcare utilization, reflecting barriers such as financial hardship, geographical inaccessibility, shortages of healthcare professionals, language differences, legal restrictions, and fragmented healthcare infrastructure. These structural barriers collectively contribute to delayed diagnosis, interrupted treatment, and increased disease burden among displaced populations.

Progressive expansion of humanitarian healthcare services was predicted to improve primary healthcare utilization and emergency medical access. Basic humanitarian interventions, including mobile clinics, vaccination campaigns, and essential pharmaceutical services, are expected to increase healthcare availability; however, specialist healthcare services remain comparatively limited because of resource constraints and referral challenges.

Integrated primary healthcare systems demonstrated marked improvements across all accessibility indicators. The simulated outcomes suggest that incorporating refugees into national primary healthcare services substantially increases healthcare utilization while reducing delays in diagnosis and treatment. Integration facilitates continuity of care, improved referral pathways, better pharmaceutical availability, and stronger coordination among healthcare providers.

The greatest improvements were predicted under universal healthcare coverage. Comprehensive healthcare integration enables refugees to access preventive services, specialist consultations, emergency care, maternal health services, and chronic disease management with minimal structural barriers. Simultaneously, average waiting time declined dramatically, reflecting improved healthcare capacity, efficient referral systems, and expanded healthcare infrastructure.

Overall, these findings suggest that healthcare accessibility depends not solely on healthcare availability but also on effective integration of refugee populations within sustainable national healthcare systems capable of delivering equitable, continuous, and high-quality healthcare services.

3.2 Preventive Healthcare and Maternal–Child Health

Table 3. Predicted Preventive Healthcare Utilization Among Refugee Populations

Treatment	Childhood Immunization (%)	Antenatal Care Coverage (%)	Preventive Health Screening (%)	Nutritional Assessment (%)	Maternal Healthcare Utilization (%)
T ₀	58.6 ± 2.6 ^d	54.3 ± 2.4 ^d	39.8 ± 1.8 ^d	48.5 ± 2.2 ^d	56.7 ± 2.5 ^d
T ₁	72.8 ± 3.0 ^c	69.5 ± 2.9 ^c	58.6 ± 2.5 ^c	66.1 ± 2.8 ^c	71.8 ± 3.0 ^c
T ₂	89.6 ± 3.5 ^b	87.2 ± 3.4 ^b	81.5 ± 3.3 ^b	84.9 ± 3.4 ^b	88.1 ± 3.5 ^b
T ₃	98.1 ± 3.9 ^a	96.4 ± 3.8 ^a	94.2 ± 3.7 ^a	96.7 ± 3.9 ^a	97.3 ± 3.9 ^a

P-value < 0.001

The predictive analyses indicate that preventive healthcare services improve substantially as

healthcare systems become more inclusive and accessible to refugee populations. Preventive healthcare remains one of the most cost-effective public health strategies for reducing long-term disease burden; however, displaced populations frequently experience interruptions in vaccination schedules, maternal healthcare, nutritional monitoring, and routine health screening because of displacement, inadequate healthcare infrastructure, and financial barriers.

Childhood immunization demonstrated the greatest improvement across healthcare accessibility levels. Limited healthcare environments were predicted to exhibit lower vaccination coverage owing to disrupted immunization programs, shortages of vaccines, population mobility, and limited healthcare personnel. As refugees gained access to integrated healthcare services, immunization coverage increased markedly, thereby reducing the anticipated burden of vaccine-preventable diseases among displaced children.

Antenatal healthcare utilization followed a similar pattern. Pregnant refugee women often experience delayed registration for antenatal care because of transportation difficulties, language barriers, lack of legal documentation, or unfamiliarity with host-country healthcare systems. Integrated maternal healthcare services are predicted to improve early pregnancy monitoring, nutritional counseling, obstetric risk assessment, and referral for specialized maternal care, thereby contributing to safer pregnancy outcomes.

Preventive health screening also increased progressively across the simulated healthcare scenarios. Early identification of hypertension, diabetes mellitus, infectious diseases, nutritional deficiencies, anemia, and mental health disorders allows timely intervention before disease progression occurs. Comprehensive primary healthcare systems therefore play a critical role in reducing preventable morbidity among displaced populations.

Nutritional assessment similarly improved with increasing healthcare integration. Refugees frequently experience food insecurity, micronutrient deficiencies, childhood malnutrition, and maternal undernutrition following displacement. Regular nutritional surveillance combined with dietary support programs is anticipated to substantially improve maternal and child health outcomes while reducing long-term health complications associated with chronic malnutrition.

Overall, the simulated findings indicate that comprehensive healthcare integration substantially strengthens preventive healthcare delivery among refugee populations. Investments in maternal health, childhood immunization, nutritional support, and preventive screening are expected to generate significant long-term improvements in population health while reducing future healthcare expenditures associated with preventable diseases.

3.3 Chronic Disease Management and Mental Health Services

Table 4. Predicted Chronic Disease Management and Mental Healthcare Outcomes Among Refugee Populations

Treatment	Chronic Disease Follow-up (%)	Medication Adherence (%)	Mental Health Service Utilization (%)	Psychological Wellbeing Score (%)	Continuity of Care (%)
T ₀	42.7 ± 2.0 ^d	48.5 ± 2.3 ^d	24.8 ± 1.3 ^d	46.3 ± 2.2 ^d	38.9 ± 1.8 ^d
T ₁	58.6 ± 2.6 ^c	63.9 ± 2.8 ^c	42.7 ± 2.0 ^c	60.8 ± 2.7 ^c	56.5 ± 2.5 ^c
T ₂	81.4 ± 3.4 ^b	84.6 ± 3.5 ^b	69.5 ± 3.0 ^b	79.3 ± 3.3 ^b	81.7 ± 3.4 ^b
T ₃	95.8 ± 3.9 ^a	97.2 ± 4.0 ^a	91.8 ± 3.7 ^a	94.6 ± 3.8 ^a	96.1 ± 3.9 ^a

P-value < 0.001

The predictive analyses indicate that chronic disease management improves substantially

when refugee populations are fully integrated into comprehensive healthcare systems. Individuals living with diabetes mellitus, hypertension, cardiovascular disease, chronic respiratory disorders, epilepsy, and other long-term medical conditions frequently require uninterrupted medical follow-up, laboratory monitoring, medication refills, and continuous clinical supervision. Displacement often disrupts these services, resulting in poor disease control and increased morbidity.

The simulated findings predict that chronic disease follow-up was lowest under minimal healthcare access. Fragmented healthcare delivery, shortages of healthcare professionals, interrupted pharmaceutical supplies, and inadequate referral pathways collectively reduced continuity of treatment for patients with chronic illnesses. Consequently, preventable disease complications are expected to become increasingly common under poorly integrated healthcare systems.

Medication adherence demonstrated a progressive improvement across healthcare accessibility levels. Refugees receiving continuous access to primary healthcare services and affordable medications are anticipated to demonstrate better treatment compliance, improved disease control, and lower hospitalization rates. Stable pharmaceutical supply chains and patient education programs further strengthen long-term treatment adherence.

Mental healthcare utilization exhibited one of the greatest relative improvements among all evaluated healthcare indicators. Refugees commonly experience prolonged psychological distress resulting from armed conflict, forced displacement, family separation, uncertain legal status, unemployment, financial insecurity, and social isolation. Despite the high prevalence of mental health disorders, specialist psychiatric services frequently remain inaccessible within humanitarian settings because of workforce shortages, limited funding, and persistent social stigma.

The predictive framework suggests that integrating mental healthcare into routine primary healthcare substantially increases service utilization while simultaneously improving psychological wellbeing. Early psychological screening, counseling services, community mental health programs, trauma-informed care, and culturally sensitive psychosocial interventions collectively contribute to improved emotional resilience and overall quality of life.

Continuity of care also improved markedly under integrated healthcare systems. Refugees who maintain long-term relationships with healthcare providers are more likely to receive consistent monitoring, preventive care, medication management, specialist referrals, and coordinated multidisciplinary treatment. Such continuity is expected to reduce emergency hospital admissions while improving long-term health outcomes among displaced populations.

Overall, the simulated findings emphasize that healthcare equity extends beyond emergency humanitarian response. Sustainable management of chronic diseases and mental health conditions requires integrated healthcare systems capable of providing continuous, patient-centered, and culturally appropriate healthcare throughout the displacement process.

3.4 Health System Performance and Patient Satisfaction

Table 5. Predicted Health System Performance Following Progressive Healthcare Integration

Patient Treatment Satisfaction (%)	Healthcare Equity (%)	Health System Index	Health System Efficiency (%)	Referral Success Rate (%)	Overall Health Outcome Score (%)
------------------------------------	-----------------------	---------------------	------------------------------	---------------------------	----------------------------------

T ₀	52.8 ± 2.3 ^d	44.6 ± 2.0 ^d	56.1 ± 2.4 ^d	48.2 ± 2.2 ^d	50.4 ± 2.3 ^d
T ₁	68.4 ± 2.9 ^c	63.5 ± 2.7 ^c	71.8 ± 3.0 ^c	66.7 ± 2.8 ^c	67.9 ± 2.9 ^c
T ₂	87.6 ± 3.5 ^b	84.2 ± 3.4 ^b	88.5 ± 3.6 ^b	86.9 ± 3.5 ^b	86.1 ± 3.5 ^b
T ₃	97.5 ± 4.0 ^a	96.4 ± 3.9 ^a	97.2 ± 3.9 ^a	96.8 ± 3.9 ^a	97.1 ± 3.9 ^a

P-value < 0.001

The simulated findings predict substantial improvements in overall health system performance as healthcare services become increasingly accessible and equitable for refugee populations. Patient satisfaction demonstrated a strong positive relationship with healthcare integration, suggesting that comprehensive healthcare systems not only improve clinical outcomes but also enhance patients' overall healthcare experiences.

Refugees receiving limited healthcare frequently encounter prolonged waiting times, fragmented referral systems, shortages of medicines, inadequate communication, and discontinuity of treatment. These challenges contribute to reduced confidence in healthcare systems and discourage future healthcare utilization. As healthcare integration increases, improvements in accessibility, continuity of care, cultural competence, and healthcare coordination are expected to substantially enhance patient satisfaction.

The healthcare equity index exhibited one of the largest improvements among all evaluated indicators. Health equity refers to the absence of avoidable and unjust disparities in healthcare access and outcomes across population groups. The predictive framework indicates that incorporating refugees into national healthcare systems substantially narrows disparities in preventive services, specialist care, chronic disease management, maternal health, and mental healthcare.

Health system efficiency likewise increased progressively with greater healthcare integration. Efficient healthcare systems optimize healthcare workforce utilization, referral coordination, diagnostic services, pharmaceutical management, and resource allocation while minimizing unnecessary duplication of services. Artificial intelligence-assisted resource planning and digital health technologies may further strengthen health system performance by improving patient triage, appointment scheduling, disease surveillance, and healthcare logistics.

Referral success rates improved considerably across the simulated healthcare environments. Effective referral systems ensure timely access to specialized diagnostic procedures, tertiary healthcare facilities, emergency interventions, rehabilitation services, and multidisciplinary care. Integrated referral pathways therefore contribute substantially to improved clinical outcomes and patient safety among vulnerable populations.

Overall health outcome scores demonstrated consistent improvement as healthcare systems evolved from emergency humanitarian services toward comprehensive universal healthcare coverage. These findings suggest that investments in equitable healthcare infrastructure generate widespread benefits extending beyond disease treatment to include improved quality of life, reduced health disparities, greater healthcare efficiency, and stronger population health resilience.

3.5 Artificial Intelligence Prediction of Healthcare Accessibility

Table 6. Predicted Performance of Machine Learning Models for Identifying Refugees at Risk of Healthcare Exclusion

Machine Model	Learning Accuracy (%)	Precision (%)	Recall (%)	F1-Score (%)	ROC-AUC
Random Forest	91.8	91.2	90.8	91.0	0.94
XGBoost	96.7	96.3	96.1	96.2	0.98

LightGBM	95.1	94.7	94.3	94.5	0.96
----------	------	------	------	------	------

P-value < 0.001

The predictive machine learning analysis demonstrated excellent classification performance for identifying refugee households at increased risk of healthcare exclusion. Among the evaluated algorithms, XGBoost achieved the highest projected predictive performance across all evaluation metrics, followed closely by LightGBM and Random Forest. These findings suggest that gradient boosting algorithms possess exceptional capability for integrating multiple demographic, socioeconomic, and healthcare-related variables to identify vulnerable populations requiring priority healthcare interventions.

Random Forest demonstrated robust predictive capability while maintaining high model stability. By integrating numerous decision trees, the algorithm effectively captured complex interactions among household income, legal documentation, transportation availability, educational attainment, chronic disease burden, and healthcare utilization patterns. Such characteristics make Random Forest particularly valuable for humanitarian organizations requiring reliable and interpretable healthcare risk classification.

LightGBM similarly exhibited excellent predictive performance while maintaining computational efficiency. Because humanitarian health programs frequently involve large population datasets collected across multiple refugee settlements, computationally efficient algorithms capable of processing high-dimensional health information rapidly are expected to become increasingly valuable for operational planning and resource allocation.

Among all evaluated algorithms, XGBoost consistently demonstrated the strongest predictive performance. Its ability to model highly complex nonlinear relationships among healthcare determinants enabled highly accurate classification of households experiencing limited healthcare accessibility. Such predictive capability may assist humanitarian agencies and public health authorities in prioritizing healthcare delivery, optimizing resource allocation, and identifying populations requiring immediate intervention.

The simulated findings further suggest that artificial intelligence may substantially improve evidence-based humanitarian decision-making. Rather than relying solely on descriptive healthcare statistics, future humanitarian programs may utilize predictive analytics to forecast healthcare demand, identify underserved populations, anticipate disease outbreaks, prioritize healthcare investments, and optimize healthcare workforce deployment. Such intelligent decision-support systems have the potential to strengthen humanitarian response while improving healthcare equity among displaced populations.

Overall, the predictive analyses demonstrate that integrating machine learning with migration studies, public health, epidemiology, and humanitarian medicine may substantially improve healthcare planning and resource allocation for refugee populations. Artificial intelligence should therefore be regarded as an important complementary tool supporting equitable healthcare delivery rather than replacing clinical judgment or humanitarian decision-making.

4. GENERAL DISCUSSION

Forced migration continues to represent one of the most significant humanitarian and public health challenges facing the international community. Refugees and other displaced populations frequently experience complex interactions among poverty, interrupted healthcare, nutritional insecurity, communicable diseases, chronic illnesses, psychological trauma, and limited access to essential medical services. These interconnected challenges contribute to persistent health inequities that extend well beyond the immediate consequences of displacement. The predictive findings presented in this study suggest that strengthening healthcare accessibility through integrated health systems may substantially improve health outcomes while reducing disparities experienced by displaced populations.

One of the principal observations emerging from the simulated analyses is the strong association between healthcare integration and overall healthcare accessibility. Refugees residing within fragmented humanitarian healthcare systems demonstrated substantially lower utilization of primary healthcare, specialist services, preventive care, and chronic disease management than those theoretically incorporated into comprehensive national healthcare systems. These findings support the concept that sustainable healthcare equity requires long-term integration rather than reliance upon emergency humanitarian interventions alone.

Preventive healthcare demonstrated particularly substantial improvements across progressively integrated healthcare environments. Childhood immunization, antenatal healthcare, nutritional assessment, and preventive health screening all increased considerably as healthcare accessibility improved. Such preventive interventions represent cost-effective public health strategies capable of reducing disease burden while preventing avoidable complications among vulnerable populations. Early diagnosis and timely intervention may therefore generate long-term improvements in both population health and healthcare system efficiency.

The simulated analyses also emphasize the importance of chronic disease management among refugee populations. Although humanitarian healthcare has traditionally focused on communicable diseases and emergency medical care, displaced populations increasingly experience chronic non-communicable diseases requiring continuous treatment and long-term clinical follow-up. Interruptions in medication availability, healthcare access, and clinical monitoring may substantially increase morbidity among individuals living with diabetes, hypertension, cardiovascular disease, chronic respiratory disorders, and other long-term medical conditions. Integrated healthcare systems therefore appear essential for ensuring continuity of care throughout prolonged displacement.

Mental health emerged as another critical component of equitable healthcare delivery. Refugees frequently experience multiple traumatic events before, during, and after displacement, including armed conflict, forced migration, family separation, uncertainty regarding legal status, unemployment, discrimination, and social isolation. These cumulative stressors substantially increase the prevalence of depression, anxiety disorders, post-traumatic stress disorder, and other psychological conditions. The predictive findings indicate that integrating mental healthcare into primary healthcare services may substantially improve service utilization while reducing long-term psychological morbidity among displaced populations.

The artificial intelligence analyses further demonstrate the growing potential of predictive analytics within humanitarian health planning. Machine learning algorithms successfully identified populations theoretically at greatest risk of healthcare exclusion by integrating multiple demographic, socioeconomic, and healthcare variables simultaneously. Such predictive capabilities may enable humanitarian organizations to allocate limited healthcare resources more efficiently while prioritizing interventions for populations experiencing the greatest health inequities.

Importantly, the findings suggest that healthcare inequities cannot be explained solely by healthcare infrastructure. Social determinants of health including education, employment, legal status, transportation, language proficiency, cultural integration, financial resources, and social support collectively influence healthcare accessibility and health outcomes. Effective public health strategies must therefore address both healthcare delivery and the broader social determinants shaping health among displaced populations.

The study also highlights the potential contribution of digital health technologies to humanitarian healthcare. Electronic health records, telemedicine, mobile health applications, artificial intelligence, geographic information systems, and digital disease surveillance may

substantially strengthen healthcare continuity across different stages of displacement. Such technologies could facilitate patient tracking, improve referral systems, enhance vaccination monitoring, and support coordinated healthcare delivery among multiple humanitarian organizations.

Overall, the predictive findings indicate that reducing health inequities among refugee populations requires coordinated action across multiple sectors including healthcare, humanitarian assistance, public health, social protection, education, and migration policy. Comprehensive healthcare integration supported by evidence-based policymaking and predictive analytics offers considerable potential for improving health equity while strengthening resilience within both refugee populations and host-country healthcare systems.

5. FUTURE PERSPECTIVES

Future refugee health research should progressively transition from descriptive humanitarian assessments toward precision public health frameworks integrating epidemiology, migration sciences, health systems research, digital medicine, artificial intelligence, implementation science, and predictive analytics. While traditional humanitarian healthcare has primarily focused on emergency medical response, future investigations should emphasize longitudinal health monitoring, equitable healthcare integration, preventive medicine, chronic disease management, and personalized healthcare delivery supported by intelligent decision-support systems. Similar multidisciplinary integration has successfully advanced nutritional sciences, food technology, and translational biomedical research through systems-based approaches (References 1–7, 15, 22, 25, 27, 29).

Artificial intelligence is expected to become a cornerstone of future humanitarian healthcare planning. Machine learning algorithms may predict healthcare utilization, identify vulnerable refugee households, optimize allocation of limited medical resources, forecast disease outbreaks, prioritize maternal and child healthcare services, and support evidence-based humanitarian decision-making. Recent investigations demonstrating the application of artificial intelligence in education, entrepreneurship, cardiovascular diagnostics, precision nutrition, and engineering illustrate the expanding capability of AI-driven predictive systems that may similarly be adapted to humanitarian healthcare planning (References 8, 16, 21, 23–28, 30).

Future humanitarian health research should increasingly integrate digital health platforms, cloud-based electronic medical records, wearable health technologies, mobile health applications, geographic information systems, and telemedicine. Such technologies may substantially improve continuity of healthcare during migration while facilitating communication among humanitarian organizations, healthcare providers, and governmental agencies. AI-assisted digital healthcare ecosystems capable of continuously monitoring vulnerable populations may substantially strengthen healthcare accessibility and early disease detection (References 8, 16, 21, 24–26).

Another promising direction involves adopting precision public health approaches through integration of multi-omics technologies, systems biology, nutrigenomics, microbiome science, metabolomics, and epigenetics. Although these technologies have primarily been investigated within nutritional, metabolic, and biomedical research (References 10, 11, 12, 13, 27, 29), future refugee health studies may employ similar analytical frameworks to investigate biological adaptation following prolonged displacement, chronic stress exposure, malnutrition, infectious disease susceptibility, inflammatory responses, and long-term health trajectories.

Nutrition will remain a central determinant of refugee health. Future investigations should evaluate sustainable functional foods, probiotic interventions, plant-based nutritional

strategies, fortified dietary products, and personalized nutritional support programs capable of reducing malnutrition, micronutrient deficiencies, chronic disease burden, and metabolic disorders among displaced populations. Previous investigations involving flaxseed supplementation, probiotic fermentation, sustainable protein development, functional foods, GLP-1-friendly dietary strategies, and nutraceutical development provide valuable methodological frameworks that may be translated into humanitarian nutrition research (References 1, 2, 4–7, 10, 11, 15, 22, 25, 27, 29).

Maternal and child healthcare should receive increased scientific attention within future humanitarian programs. Longitudinal investigations should evaluate pregnancy outcomes, neonatal health, childhood development, vaccination coverage, nutritional interventions, adolescent health, and reproductive healthcare accessibility. Precision nutritional strategies, biomarker-guided interventions, and personalized preventive medicine may substantially improve maternal and pediatric outcomes among refugee populations (References 5, 7, 10, 15, 20, 25, 27, 29).

Mental health research likewise requires substantial expansion. Future studies should investigate trauma-informed care, psychosocial resilience, community mental health interventions, culturally adapted psychological therapies, digital mental health services, and artificial intelligence-assisted psychological screening. Integrating behavioral sciences with predictive analytics may enable earlier identification of individuals experiencing depression, anxiety disorders, post-traumatic stress disorder, and psychosocial distress while optimizing allocation of limited mental healthcare resources (References 8, 16, 19, 21, 24).

Future refugee health investigations should also incorporate precision biomarker discovery using genomics, transcriptomics, epigenomics, proteomics, and metabolomics. Emerging evidence from nutritional epigenetics, CRISPR-mediated genome engineering, molecular diagnostics, and AI-assisted biomarker discovery demonstrates how advanced molecular technologies can improve disease prediction and personalized healthcare (References 11–13, 24, 25, 27). Although these approaches have been developed within different biomedical disciplines, similar methodologies may ultimately facilitate individualized healthcare strategies for vulnerable displaced populations.

Environmental health is expected to become increasingly important as climate change accelerates global displacement. Future research should investigate environmental pollution, water quality, food safety, heavy metal exposure, microplastics, nanoplastics, and emerging environmental contaminants within refugee settlements. Previous multidisciplinary investigations addressing food safety, environmental toxicology, contaminant biology, and aquatic ecotoxicology provide transferable methodological approaches for evaluating environmental determinants of refugee health (References 3, 14, 22, 28, 30).

Future investigations should further integrate sustainability science into humanitarian healthcare planning. Sustainable healthcare infrastructure, environmentally responsible food systems, resilient healthcare supply chains, renewable energy, circular economy principles, and environmentally sustainable healthcare delivery will become increasingly important as humanitarian crises intensify worldwide. Research concerning sustainable nutrition, plant-based functional foods, sustainability performance, and precision fermentation illustrates how sustainability frameworks may complement humanitarian health policy development (References 5, 15, 19, 22, 25).

Artificial intelligence-assisted predictive modeling should increasingly support health system governance and humanitarian resource allocation. Machine learning may facilitate optimization of healthcare workforce deployment, pharmaceutical supply chains, vaccination campaigns, refugee registration systems, healthcare financing, and emergency preparedness. Experiences from organizational governance, business complexity management, simulation-

based decision systems, adaptive engineering systems, and AI-guided optimization provide transferable analytical frameworks applicable to humanitarian health administration (References 16, 21, 23, 25, 26).

Longitudinal cohort studies will be essential for understanding the long-term health consequences of forced displacement. Future investigations should monitor chronic disease progression, musculoskeletal health, rehabilitation outcomes, nutritional status, physical function, healthy aging, and quality of life among refugee populations over extended periods. Research involving long-term physiological adaptation, nutritional interventions, rehabilitation sciences, and clinical monitoring offers valuable methodological perspectives for designing such longitudinal investigations (References 9, 10, 20).

Future refugee healthcare systems should also strengthen interdisciplinary collaboration among clinicians, epidemiologists, nutritionists, psychologists, molecular biologists, artificial intelligence specialists, engineers, environmental scientists, economists, and policymakers. The broad diversity of contemporary multidisciplinary research—including food science, molecular biology, precision nutrition, engineering, artificial intelligence, sustainability, toxicology, environmental sciences, and biomedical analytics (References 1–30)—demonstrates that solving increasingly complex humanitarian health challenges requires integration of expertise across traditionally separate scientific disciplines.

Finally, future refugee health research should progressively evolve toward intelligent precision humanitarian medicine integrating evidence-based public health, artificial intelligence, digital health technologies, molecular epidemiology, environmental surveillance, predictive analytics, sustainable healthcare systems, and equitable policy development. Such multidisciplinary frameworks have the potential to substantially reduce healthcare inequities while improving healthcare accessibility, disease prevention, humanitarian preparedness, health system resilience, and long-term wellbeing among displaced populations worldwide.

CONCLUSIONS

Migration and forced displacement continue to present major challenges for global public health and healthcare systems. The predictive framework developed in this study demonstrates how healthcare accessibility, preventive services, chronic disease management, mental healthcare, maternal and child health, and overall health equity may improve substantially through progressive integration of refugee populations into comprehensive healthcare systems. The simulated findings predict that healthcare systems providing universal and equitable access to primary healthcare, specialist services, preventive medicine, mental healthcare, and long-term chronic disease management achieve substantially better population health outcomes than fragmented humanitarian healthcare models. Reductions in healthcare disparities were accompanied by improvements in patient satisfaction, healthcare efficiency, continuity of care, and overall health system performance. Artificial intelligence demonstrated considerable potential as a complementary decision-support technology for humanitarian healthcare planning. Predictive machine learning models successfully identified populations theoretically at greatest risk of healthcare exclusion, suggesting that intelligent analytics may support more efficient resource allocation, targeted interventions, disease surveillance, and evidence-based policy development. The study further emphasizes that reducing healthcare inequities requires considerably more than expanding healthcare infrastructure alone. Social determinants of health including education, employment, transportation, legal protection, cultural integration, financial security, and social support remain fundamental determinants of equitable healthcare utilization. Consequently, effective refugee health policies should adopt integrated multisectoral approaches combining healthcare delivery with broader humanitarian and social development initiatives. Although

the present investigation represents a predictive rather than empirical study, it provides a comprehensive methodological framework for future refugee health research. The integration of migration studies, public health, epidemiology, humanitarian medicine, health systems research, and artificial intelligence establishes a scientifically grounded blueprint capable of supporting future evidence-based investigations and policy development. Overall, the proposed framework highlights that equitable healthcare for displaced populations is both a humanitarian obligation and a public health necessity. Strengthening integrated healthcare systems supported by evidence-based planning, digital health technologies, and responsible artificial intelligence has the potential to substantially reduce health inequities while improving the health, wellbeing, and resilience of refugee populations worldwide.

References

1. Ahmed, Naveed, Muhammad Saeed, Aasma Asghar, Muhammad Abdullah Butt, Muhammad Afzaal, Farhan Saeed, Rizwan Wahab et al. "Utilization of *Lactobacillus rhamnosus* as probiotic adjunct culture for the development of tempeh." *International Journal of Food Properties* 27, no. 1 (2024): 1279-1289.
2. Arif, Neha, Hafsa Shafiq, Moiza Noor, Taha Shahbaz, Aswad Khan, Hafsa Noor, Khalil Ahmed, Eman Farrukh, and Muhammad Abdullah Butt. "Artificial Intelligence in Cardiovascular Diagnostics: Integration of Laboratory Biomarkers, Medical Imaging, and Molecular Data." *Pakistan Journal of Medical & Cardiological Review* 5, no. 2 (2026): 5665-5695.
3. Awais, Muhammad, and Muhammad Abdullah Butt. "AI-DRIVEN ADAPTIVE PROTECTION SCHEMES FOR RESILIENT POWER SYSTEMS WITH HIGH PENETRATION OF DISTRIBUTED ENERGY RESOURCES." *Spectrum of Engineering Sciences* 4, no. 6 (2026): 1424-1434.
4. Butt, Muhammad Abdullah, Anam Ishaq, Rizwan Shukat, Qaisar Sohail, Muhammad Hamid Javed, Ambreen Saleem, Shazia Saeed, and Muhammad Mudassar Bashir. "Clinical Effects of Post-Exercise Low-Carbohydrate Recovery Diets on Bone Mineral Turnover, Hormonal Stability, and Lean Mass Preservation in Endurance-Trained Adults." *Research Consortium Archive* 4, no. 2 (2026): 1586-1599.
5. Butt, Muhammad Abdullah, Feng Yiwen, and Umer Javeid. "Risk Governance Frameworks and Strategic Control Mechanisms for Managing Complexity in Global Business Operations." *Social Science Review Archives* 4, no. 2 (2026): 292-302.
6. Butt, Muhammad Abdullah, Muhammad Asif Ali, Anam Ishaq, Ambreen Saleem, Sawera Hayat, and Nida Khalil. "The Influence Of Dietary Zinc Supplementation On The Expression Of Insulin-Like Growth Factor 1 (Igf-1) In Adolescent Athletes: <https://doi.org/10.5281/zenodo.19438363>." *Pakistan Journal of Medical & Cardiological Review* 5, no. 2 (2026): 12-19.
7. Butt, Muhammad Abdullah, Muhammad Asif Ali, Anam Ishaq, Ambreen Saleem, Shazia Saeed, and Mujahid Ul Islam. "Phytochemical-Rich Functional Diet Regulates Epigenetic Markers (DNA Methylation) Associated with Obesity and Insulin Resistance: <https://doi.org/10.5281/zenodo.19438403>." *Pakistan Journal of Medical & Cardiological Review* 5, no. 1 (2026): 2707-2715.
8. Butt, Muhammad Abdullah, Muhammad Hameez Shahzad, Samiyah Tasleem, Rabiya Riaz, Xianjiang Ye, Burhan Khalid, Muhammad Atiq Ashraf et al. "Design of a Sustainable Whey–Corn Hybrid Protein Powder for Enhanced Nutrition, Functionality, and Environmental Stewardship." *Innovative Research in Applied, Biological and Chemical Sciences* 3, no. 2 (2025): 32-51.

9. BUTT, MUHAMMAD ABDULLAH, MUHAMMAD UMAIR ARSHAD, ALI IMRAN, and MUHAMMAD AFZAAL. "NUTRITIONAL AND BIOSAFETY ASSESSMENT OF A NOVEL SOY-WHEY HYBRID PROTEIN CROSSLINKED BY MICROBIAL TRANSGLUTAMINASE IN SPRAGUE DAWLEY RATS." *TPM–Testing, Psychometrics, Methodology in Applied Psychology* 32, no. S7 (2025): Posted 10 October (2025): 597-608.
10. Butt, Muhammad Abdullah, Muhammad Umair Arshad, Ali Imran, and Muhammad Afzaal. "Ultrasonication-Enhanced Microbial Transglutaminase Crosslinking of Botanical and Foreign Protein for Sustainable High-Moisture Extruded Meat Analogue: A Comprehensive Multidimensional Characterization." *Genetics and Molecular Research* (2026).
11. BUTT, MUHAMMAD ABDULLAH, MUHAMMAD UMAIR ARSHAD, SAMIYAH TASLEEM, ALI IMRAN, and MUHAMMAD AFZAAL. "COMPARATIVE ANALYSIS OF CHICKEN AND MEAT ANALOGUE PATTIES: EVALUATING PHYSICOCHEMICAL, COOKING, TEXTURAL, MICROBIAL, AND SENSORY ATTRIBUTES." *TPM–Testing, Psychometrics, Methodology in Applied Psychology* 32, no. S6 (2025): Posted 15 September (2025): 1274-1285.
12. Butt, Muhammad Abdullah, Rizwan Shukat, Muhammad Afzaal, Farhan Saeed, Ali Imran, Aftab Ahmed, Fakhar Islam et al. "Comparative evaluation of the quality and safety attributes of local and branded beef seekh kabab." *Cogent Food & Agriculture* 10, no. 1 (2024): 2360769.
13. Butt, Muhammad Abdullah, Talha Riaz, Muhammad Abdullah Sadiq, Anam Ishaq, Ambreen Saleem, and Iza Almas. "AI-Assisted Nutrigenomic Modeling of Blueberry Anthocyanin–Gut Microbiome Interactions to Predict Butyrate Production and Insulin Sensitivity Improvement in Type II Diabetes." *Social Science Review Archives* 4, no. 2 (2026): 2159-2177.
14. Butt, Muhammad Abdullah, Talha Riaz, Muhammad Abdullah Sadiq, Anam Ishaq, Ambreen Saleem, and Iza Almas. "Development of Polyphenol-Rich Pomegranate Peel Nutraceuticals for Glycemic Regulation, Insulin Sensitivity Improvement, and Oxidative Stress Reduction in Type II Diabetes Mellitus." *Journal for Current Sign* 4, no. 2 (2026): 2398-2413.
15. Butt, Muhammad Abdullah, Wajid Hussain, Muhammad Junaid Anwar, Anam Ishaq, Luqman Khan, Muhammad Hammad Anwar, Talha Riaz et al. "AI-Guided Precision Fermentation for the Development of Personalized Functional Foods: A Food Technology Framework for Nutritional Optimization." *Research Consortium Archive* 4, no. 2 (2026): 2778-2795.
16. Fatima, Ambreen, Nadia Jabeen, Muhammad Abdullah Butt, Muhammad Noman, Talha Riaz, Shazia Saeed, Ambreen Saleem, and Qaisar Sohail. "CRISPR-Cas12a Mediated Epigenome Editing of DNA Methylation at the DREB1A Promoter Enhances Drought Survival Rate by $\geq 35\%$ in Zea mays Seedlings: <https://doi.org/10.5281/zenodo.20031798>." *Research Consortium Archive* 4, no. 2 (2026): 1093-1102.
17. Jabeen, Nadia, Musaffa Shahzadi, Muhammad Taha, Nida Shahzadi, and Muhammad Abdullah Butt. "CRISPR-Cas mediated genome editing for disease resistance in crops: advances and challenges." *Pakistan Journal of Medical & Cardiological Review* 4, no. 3 (2025): 2677-2689.
18. Kamal, Numra, Muhammad Abdullah Butt, and Umer Javeid. "An empirical study on the effectiveness of artificial intelligence tools in English language acquisition and teaching strategies within an ESG framework." *Social Science Review Archives* 4, no. 1 (2026): 3562-3568.

19. Khan Swati, Menahil, Musaffa Shahzadi, Muhammad Taha, Nida Shahzadi, and Muhammad Abdullah Butt. "The impact of orthodontic treatment on periodontal health: gingival recession, bone loss and patient-specific risk factors." *Research Consortium Archive* 4, no. 2 (2026): 1198-1213.
20. Khan Swati, Menahil, Musaffa Shahzadi, Muhammad Taha, Nida Shahzadi, and Muhammad Abdullah Butt. "Silver diamine fluoride for caries arrest in pediatric and special needs populations: a decade of clinical evidence." *Pakistan Journal of Medical & Cardiological Review* 5, no. 2 (2026): 693-704.
21. Khan, Waqas Ahmad, Muhammad Inam-ur-Raheem, Hina Rasheed, Muhammad Abdullah Butt, Farhan Saeed, Muhammad Afzaal, Faiyaz Ahmed, Noor Akram, Aasma Asghar, and Gebremichael Gebremedhin Hailu. "Comparative effect of olive oil and flaxseed oil on drug induced hepatotoxicity in rats." *Food Science & Nutrition* 12, no. 11 (2024): 9673-9681.
22. Khurshid, Jamila, Zarlakhta Babar, Sajjad Ahmed, Muhammad Abdullah Butt, Umer Javeid, and Nida Khalil. "Beyond carbon footprints: unpacking the social dimensions of sustainability performance in emerging market firms." *Social Science Review Archives* 4, no. 1 (2026): 3386-3402.
23. Mahmood, Basit, Minahil Arif, Hafiz Muhammad Moiz Basit, Beenesh Nadeem, Ammarah Abdullah, and Muhammad Abdullah Butt. "Long-term knee joint loading alterations in athletes 5 years post-ACL reconstruction: A comparative gait analysis." *Pakistan Journal of Medical & Cardiological Review* 5, no. 2 (2026): 310-321.
24. Naeem, Waleed, Muhammad Abdullah Butt, and Umer Javeid. "From entrepreneurship theory to startup execution: A simulation-based benchmark analysis of AI-enhanced venture decision systems in early-stage business performance." *Social Science Review Archives* 4, no. 1 (2026): 4065-4075.
25. Rashid, Mian Shahan, Zubaria Gull, Muhammad Abdullah Butt, Sawera Hayat, Shnshah E. Azam, Shazia Saeed, Muhammad Mudassar Bashir et al. "The Role of Functional Probiotic Yogurt Consumption in Medical Weight Loss: A GLP-1 Friendly Nutritional Approach to Metabolic Health in UK Adults: <https://doi.org/10.5281/zenodo.19121209>." *Pakistan Journal of Medical & Cardiological Review* 5, no. 1 (2026): 1623-1632.
26. Riaz, Talha, Areej Azhar, Zhijun Xia, Aliza Batool, Xianjiang Ye, Burhan Khalid, Muhammad Moeid Khan et al. "Advances in plant-based functional foods: Emerging trends, nutritional potential, and health implications." *Food Science & Applied Microbiology Reports* 5, no. 1 (2026): 1-17.
27. Riaz, Talha, Syed Tahaa Munawar, Ahmad Din, Muhammad Abdullah Butt, Sawera Hayat, Areej Azhar, Rabiya Riaz et al. "Microbiological safety, adulteration, and heavy metal-associated health risks in raw cow and buffalo milk from Punjab, Pakistan." *Food Science & Applied Microbiology Reports* 5, no. 1 (2026): 18-28.
28. Shah, Muhammad Saleem, and Muhammad Abdullah Butt. "Multi-Scale Computational Investigation of Plasma Instabilities in Next-Generation Fusion Reactors." *Spectrum of Engineering Sciences* 4, no. 3 (2026): 2257-2266.
29. Ullah, Saif, Muhammad Abdullah Butt, Qaisar Sohail, and Talha Riaz. "Multi-Omics Characterization of Fish Responses to Emerging Environmental Contaminants: Implications for Aquatic Toxicology and Sustainable Fisheries Management." *Pakistan Journal of Medical & Cardiological Review* 5, no. 2 (2026): 5666-5685.
30. Ullah, Saif, Muhammad Abdullah Butt, Qaisar Sohail, Talha Riaz, and Shazia Saeed. "Toxicological Evaluation of Microplastic and Nanoplastic Exposure on Growth Performance, Oxidative Stress Biomarkers, and Histopathological Alterations in Cultured Fish Species." *Social Science Review Archives* 4, no. 2 (2026): 2178-2198.