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Table of Contents

Economic Sciences

SYNERGISTIC EFFECTS OF AI PILOT ZONES AND CLIMATE GOVERNANCE ON URBAN GREEN TRANSFORMATION: EVIDENCE FOR SUSTAINABLE URBAN DEVELOPMENT 5
KANG HUIMING

INFRASTRUCTURE SUPPORT FOR SPATIAL DEVELOPMENT OF RURAL AREAS 25
TATYANA PUPYSHEVA
NAKIPOVA GULMIRA
PUNTUS YEVGENIYA
NURAKHMETOVA ASSEMGUL

Philological Sciences

MİLLİ VƏ BEYNƏLXALQ TƏHSİL STANDARTLARININ MÜƏLLİM HAZIRLIĞINA TƏSİRİ 32
RƏFİYEVA XURAMAN ƏLİ QIZI

THE ROLE OF GLOBALIZATION IN THE FORMATION OF NATIONAL-HISTORICAL CONSCIOUSNESS..... 36
AKHMETZHANOVA A.T.

THE TATAR WOMEN'S PROSE AND POETRY IN KAZAKHSTAN..... 40
MASHAKOVA AIINUR KASSYMZHANOVNA

Medical Sciences

THE SCIENTIFIC DISCOURSE ON REDEFINING AND ENHANCING HIGHER MEDICAL PHARMACOLOGY EDUCATION FOR MEDICAL DOCTOR (MD) STUDENTS IN UNIVERSITIES: A COMPREHENSIVE EVIDENCE-BASED CONCEPTUAL FRAMEWORK INTEGRATING PHARMACOLOGY, PHARMACOTHERAPY AND CLINICAL PHARMACOLOGY THROUGH COMPETENCY-BASED, INNOVATIVE, CLINICALLY RELEVANT AND EVIDENCE-INFORMED TEACHING AND LEARNING STRATEGIES..... 44
NODAR SULASHVILI
MARGARITA BEGLARYAN
DIEGO RADA FERNANDEZ DE JAUREGUI
MAKA BULEISHVILI
MARIAM DARBAIDZE
NANA GORGASLIDZE
NATO ALAVIDZE
IRINA IMERLISHVILI
NAIRA CHICHOYAN
MARIKA SULASHVILI
MARINA GIORGOBIANI
ADA (ADEL) TADEVOSYAN
IGOR SENIUK
VIRA KRAVCHENKO
MAGDA DAVITASHVILI
OLGA SHAPOVAL
NATIA KVIZHINADZE
NINO ABULADZE
RAJKARAN SINGH
DAVID APHKHAZAVA

Biological Sciences

КІШІ АРАЛ ТЕҢІЗІНДЕГІ КӘСІПТІК БАЛЫҚТАРДЫҢ ҚАЗІРГІ ЖАҒДАЙЫ 95
ЕРМАХАНОВА Ж.З.
САФИЕВА А.А.

COMPARATIVE TRANSCRIPTOMICS AND METHYLOMICS OF REJUVENATION CAPACITY ACROSS SIX ANIMAL SPECIES 101
DAVID APHKHAZAVA
MAIA NOZADZE
MZIA TSIKLAURI
MANANA MAKHARADZE
MAIA BERODZE
NODAR SULASHVILI
GIORGI MARGVELANI
ANUSHKA ROHIDAS TEMGIRE
ARFAN IMTIAZ ABDUL SAMAD
THARUSHI ANARGALI SILVA
OLUWADAMILOLA PENTHO NUDEGBESI
MUSKAN KHAN
VEDANT ANILKUMAR MALEKAR
AAYUSHI THAKUR
JANHVI DEEPAK DOSHI
NINO MAZIASHVILI
LOLITA SHENGELIA
GEORGE MAGLAKELIDZE
ILIA ATANELISHVILI

Technical Sciences

ANGULAR OSCILLATORY SINGLE-STROKE ELECTROMAGNETIC VIBRATORY MOTOR WITH A SEMICONDUCTOR ELEMENT 119
GELA JAVAKHISHVILI
PAATA STURUA

КҮРІШ ҚАҰЫЗЫНЫҢ КҮЛІН БЕТОН ҚҰРАМЫҢДА ҚОЛДАНУ ЕРЕКШЕЛІКТЕРІ	124
---	-----

АРЫСТАНБЕК А.Б.
ҮДЕРБАЕВ С.С.

Political Studies

FRANCE'S INVESTMENTS IN KAZAKHSTAN AS AN INSTRUMENT OF ECONOMIC DIPLOMACY	134
---	-----

KAMILA OMIRBEKKYZY
AIGERIM ZHAKYANOVA

THE ROLE OF ITALY IN INFRASTRUCTURE DEVELOPMENT IN KAZAKHSTAN	142
---	-----

KAMILA OMIRBEKKYZY
AIGERIM ZHAKYANOVA

Historical Sciences

THE HISTORICAL SIGNIFICANCE OF THE SWISS REFORMATION	148
--	-----

MEHDIYEVA AYTEN ALI

Culturology

ПОСТКОЧЕВАЯ ИДЕНТИЧНОСТЬ: ЧТО ОСТАЛОСЬ ОТ КОЧЕВОГО МИРА В СОЗНАНИИ ГОРОДСКИХ КАЗАХСТАНЦЕВ XXI ВЕКА	157
--	-----

МИХАЙЛЕНКО КАРИНА АЛЕКСЕЕВНА
АНДИРЖАНОВА ГУЛЬНАР АБЫЛХАИРОВНА

TRADITIONAL 'NEW VOICE': Q-POP IN THE CULTURAL DYNAMICS OF CONTEMPORARY KAZAKHSTAN	166
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NURZHAYEVA ALINA MARATOVNA
ORAZGALI GULZHA

Economic Sciences

Synergistic Effects of AI Pilot Zones and Climate Governance on Urban Green Transformation: Evidence for Sustainable Urban Development

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Abstract: This study is a dedicated empirical investigation of the impacts of Artificial Intelligence Pilot Zones on sustainable urban development, focusing on the ecological and technological dimensions. Coordinate the promotion of digital technology empowerment and climate adaptation to advance the green economic decarbonisation of developing countries. Although previous studies have focused on digital pilots and environmental regulations separately, the spatial synergy and micro-level transmission mechanisms of technological instruments under institutional constraints have not been explored. Leveraging the spatial overlap between the National Artificial Intelligence Innovation and Development Pilot Zones and Climate-Adaptive City Pilots as a quasi-natural experiment, this paper uses a balanced panel dataset of 285 Chinese prefecture-level cities from 2000 to 2022. Based on Porter's hypothesis and the theory of technology-institution complementarity, we construct a Constraint Instrument theoretical framework and apply multi-period interaction difference-in-differences (DID), Callaway and Sant'Anna (2021) heterogeneity-robust estimators, and partially linear double machine learning (DML) to identify policy synergy. The empirical results show that policy synergy significantly reduces the intensity of urban industrial SO₂ emissions and energy-intensity per unit of GDP, with an interaction coefficient of -0.0542 ($p < 0.05$), indicating a complementary "1 + 1 > 2" decarbonisation dividend. The dynamic parallel trend assumption is verified over an extended pre-treatment window ($\tau = -5$ to $+3$) using a joint Wald test ($p = 0.702$) anchored on joint policy rollout, and anticipation effects have been ruled out. The results are consistent after controlling for the concurrent policies (Low-Carbon Cities, Smart Cities, Sponge Cities), meteorological factors (temperature and precipitation), and 500 Monte Carlo placebo runs. Disentangled mechanism analysis shows that green invention patenting (accounting for 28.6% of SO₂ reduction) and energy-saving improvements (accounting for 34.3%) are the main transmission paths, while green digital process innovation and industrial rationalisation drive energy-intensity reduction. Heterogeneity analysis shows that the synergistic dividend is significantly higher in old industrial cities (-0.0782), and high computing-density hubs show a slight, statistically non-significant decrease, indicating a computing-energy rebound effect. The above results provide empirical support and a transferable model for the development of a coordinated digital transformation and climate adaptation strategy in China. From the dual perspectives of technological innovation and ecological emission abatement, this study provides granular empirical evidence for the role of AI pilot zones in driving sustainable urban development.

Keywords: Artificial Intelligence Pilot Zones; Climate-Adaptive Cities; Policy Synergy; Green Transformation; Double Machine Learning; Staggered DID; Environmental Economics

1. Introduction

At this time in history, as the whole world moves towards carbon neutrality and artificial intelligence develops rapidly around the globe, promoting the green and low-carbon transformation of cities has become an urgent task for high-quality economic development. The two structural bottlenecks of the urban industrial system are high capital costs for green technology transformation and significant information asymmetry in climate change response. Traditional command-and-control climate policies lack fine-grained digital governance instruments; thus, there is enforcement friction, a potential reduction in output, and factor misallocation. At the same time, the rapid development of AI infrastructure is electricity-intensive and may lead to computing-related carbon leakage. Most of the previous studies have focused on single-policy pilots in isolation and have failed to consider the spatial and institutional synergies that arise when digital technology empowers people and institutions.

To address the above problems, this paper takes advantage of the spatial overlap between the National New Generation Artificial Intelligence Innovation and Development Pilot Zones (AI pilots) and Climate-Adaptive City Pilots as a quasi-natural experiment. Using a balanced panel dataset of 285 Chinese prefecture-level cities from 2000 to 2022, we systematically explore the spatial synergistic decarbonisation dividends and transmission mechanisms of the dual-policy implementation. Our research offers four main marginal contributions: First, we build a formal Constraint+Instrument theoretical system based on the Porter hypothesis and technology-institution complementarity, and formulate testable research hypotheses. Second, to address the problem of potential negative weighting bias in staggered multi-cohort settings (Goodman-Bacon, 2021), we use both multi-period interaction DID and Callaway and Sant'Anna (2021) heterogeneity-robust estimators, anchor the dynamic parallel trend on joint dual-policy rollout timing across an extended pre-treatment window ($\tau = -5$ to $+3$), and perform joint Wald pre-trend tests. Third, we build a disentangled mediation system to separate pollutant reduction channels from energy intensity mechanisms, avoid circular reasoning, and clarify post-treatment identification assumptions. Fourth, we have strictly controlled for concurrent urban environmental and digital initiatives (Low-Carbon Cities, Smart Cities, Sponge Cities) as well as meteorological factors, and employed partially linear double machine learning to partially eliminate high-dimensional non-linear confounding. This study provides empirical support for China's digital-green integrated governance and offers a replicable policy system for other developing countries facing the dual problems of digitalisation and carbon reduction.

2. Literature Review and Theoretical Foundation

1. Literature Review

Scholarship on the environmental externalities of digital transformation and climate governance has gradually developed in three main research streams:

First, Environmental Impacts of Single Digital and Climate Policies. A large body of empirical research has examined the standalone green dividend of environmental regulations and digital pilot programmes. Research in environmental economics has found that carbon targets, environmental liability insurance and command-and-control regulations have motivated enterprises to reduce industrial emissions and promoted green patenting (Sun et al., 2025; Wu, 2025). Concurrently, scholars examine digital technology pilots, demonstrating that artificial intelligence and digital infrastructure enhance industrial energy efficiency and optimize production scheduling (Liang et al., 2026). Digital monitoring platforms further reduce the problem of information asymmetry in regulatory enforcement decay (West et al., 2025). Climate-adaptive city pilots aim to strengthen the climate resilience of cities, and recent studies have

shown that the adaptation infrastructure provides substantial "co-benefits" by reducing the cost of industrial emission abatement (Li et al., 2025; Zhu & Rastelli, 2025).

Second, Multi-policy Synergy and Complementary Governance. Recently, scholars have begun to study whether the new public policies are in harmony or conflict with one another (Yang & Tol, 2025). In the absence of technology, environmental constraints will lead to temporary production reductions rather than long-term decarbonisation by the firm. Conversely, when digital technology develops freely, the Jevons paradox and computing-energy rebound will increase the total energy demand. Although recent studies have investigated the combination of market-based and regulatory tools, few have integrated the application of digital technology and institutional-climate adaptation into a unified spatial synergy system.

Third, Econometric Advances in Policy Evaluation. Methodologically, the causal evaluation of staggered multi-cohort policy pilots has seen significant progress. Traditional two-way fixed-effects (TWFE) estimators are likely to be biased towards the negative end when the treatment timing varies among units (Goodman-Bacon, 2021). To address this problem, heterogeneity-robust staggered difference-in-differences (DID) estimators have been developed to prevent earlier treated units from acting as contaminated controls for later treated units (Callaway & Sant'Anna, 2021; Leventer, 2025; Miyaji, 2025). Partially linear double machine learning (DML) can handle non-linear confounding and functional misspecification in high-dimensional data (DiTraglia & Liu, 2025; Lal & Chou, 2025; Xiang et al., 2026).

Summary of Research Gaps: In short, the existing literature has three main deficiencies: (1) most studies focus on climate adaptation and AI pilots separately, ignoring their institutional-technological synergy; (2) mechanism analysis often suffers from circular logic by employing the same indicators for both outcomes and mediators; and (3) staggered empirical evaluations frequently fail to integrate multi-cohort robust estimators with high-dimensional machine learning adjustments. This paper directly addresses these deficiencies.

2. Theoretical Foundations and Research Hypotheses

According to Porter's hypothesis, technology-institution complementarity theory and marginal abatement cost dynamics, we build a Constraint Instrument theoretical framework to formalize dual policy synergy:

(1) The Constraint Instrument Dual Policy Synergistic Mechanism

Urban green transformation needs both external regulatory pressure and internal technological capacity. Climate-adaptive city pilots generally function as institutional "administrative constraints" by setting urban climate resilience goals, infrastructure standards and ecological protection boundaries. According to Porter's hypothesis (Porter & van der Linde, 1995), an unfavourable environment of constraints will drive enterprises to increase the use of resources through innovation. Traditional command-and-control systems have high monitoring costs and information asymmetry, so they result in enforcement friction.

Conversely, the National AI Innovation Pilot Zones serve as "technological instruments" to deploy digital infrastructure, cloud computing and smart algorithms (Acemoglu et al., 2012). AI can perform high-level analysis, but by itself, digital technology does not provide an environmental goal and may increase energy consumption through computation. According to the theory of technology-institution complementarity, at the intersection of space and time, these two policy initiatives have created a "1+1 > 2" governance synergy: climate adaptation policies have established institutional boundaries and green demand scenarios to guide AI capital and algorithmic innovation towards ecological governance, and AI tools provide real-time sensing, predictive modelling and automated optimisation to reduce regulatory compliance costs significantly.

Hypothesis 1 (H1): The spatial synergy of National AI Pilot Zones and Climate-Adaptive City Pilots creates a complementary "1 + 1 > 2" decarbonisation dividend, significantly reducing urban industrial SO₂ emission intensity and energy consumption per unit of GDP.

(2) Micro-level Transmission Channels: Green Innovation and Energy Efficiency

Together, digital empowerment and climate governance work together to achieve the following two micro-level transmission paths:

Green Technology Innovation Channel: Under the standalone climate adaptation policies, industrial enterprises face compliance pressure but lack the technical ability for green R&D. AI pilot zones offer high-end computing platforms, machine learning algorithms for materials simulation, and digital knowledge spillover to reduce the cost and risk of green technology development, thus promoting green invention breakthroughs.

Energy-saving Improvement Channel: Energy waste in industrial production often results from inefficient equipment scheduling, poor thermal management, and supply-demand mismatches in utility grids. AI-powered digital platforms can perform real-time parameter adjustment, predictive maintenance and dynamic load balancing of industrial systems. Digitalisation reduces per-unit energy waste in conjunction with the urban climate adaptation energy-efficiency benchmark.

Hypothesis 2a (H2a): Policy synergy promotes urban green transformation by stimulating green invention patenting and technological innovation.

Hypothesis 2b (H2b): Policy synergy can reduce industrial emissions by enhancing energy-saving in-use efficiency and optimising production process scheduling.

(3) Structural Heterogeneity: Industrial Legacy and Computing Rebound

The net environmental benefits of the dual-policy system are determined by the urban industrial legacy and the energy characteristics of the digital infrastructure.

Heterogeneity of Industrial Backgrounds: Based on the theory of marginal abatement costs, older industrial cities and resource-depleted areas have historically borne a heavy burden of carbon-intensive manufacturing and obsolete equipment. AI tools in these cities have achieved only marginal improvements in energy retrofitting and smart end-of-pipe monitoring for climate adaptation scenarios, generating relatively low structural remediation dividends compared with those in less carbon-intensive, modern service-oriented cities.

Computing Infrastructure Energy Rebound: Although artificial intelligence is being used to promote green development, the construction of large-scale data centres, computing clusters and server facilities is also energy-intensive. Under the Jevons paradox, in cities with high computing density, a high Power Usage Effectiveness (PUE) and continuous electricity demand can lead to an energy rebound effect and reduce the decarbonisation benefit of digitalisation.

Hypothesis 3a (H3a): The synergistic green transformation dividend is relatively larger in old industrial base cities with a high marginal abatement potential.

Hypothesis 3b (H3b): High computing-density hubs experience coefficient attenuation due to computing-infrastructure energy rebound effects.

3. Econometric Strategy, Variable Definitions and Data Sources

1. Econometric Model Specifications

(1) Multi-period Interaction Difference-in-Differences (DID) Baseline Model

To identify the spatial synergistic effect of the dual policy pilots on urban green transformation, we specify the following multi-period panel fixed-effects DID model:

$$Y_{it} = \alpha_0 + \beta_1 AI_{it} + \beta_2 Climate_{it} + \beta_3 (AI_{it} \times Climate_{it}) + \sum_{k=1}^K \gamma_k X_{kit} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

Table 1: Mathematical Parameter Definitions and Econometric Interpretation for the Baseline DID Model

Parameter / Symbol	Mathematical Definition and Econometric Interpretation
Y_{it}	Dependent variable representing green transformation performance of city i in year t , measured by industrial SO2 emission intensity ($SO2_{it}$, tons/10,000 RMB) and energy intensity per unit of GDP ($Energy_{it}$, tons SCE/10,000 RMB)
AI_{it}	Binary treatment indicator for National AI Innovation Pilot Zones. Equals 1 if city i is approved as an AI pilot in year t or later, and 0 otherwise
$Climate_{it}$	Binary treatment indicator for Climate-Adaptive City Pilots. Equals 1 if city i is designated as a climate pilot in year t or later, and 0 otherwise
$AI_{it} \times Climate_{it}$	Core interaction term capturing the net spatial synergistic effect of dual policy overlap
α_0	Model intercept
β_1, β_2	Independent marginal coefficients measuring the standalone impact of AI pilots and climate pilots, respectively
β_3	Primary parameter of interest. A statistically significant negative coefficient ($\beta_3 < 0$) indicates a complementary "1 + 1 > 2" abatement dividend
X_{kit}	Vector of K control variables, including secondary industry share ($SecondInd_{it}$), log real GDP per capita ($LnRealGDPpc_{it}$), urbanization rate ($UrbanRate_{it}$), fiscal self-sufficiency ($FiscalSelf_{it}$), log population density ($PopDensity_{it}$), and FDI ratio ($FDIRatio_{it}$)
γ_k	Marginal regression coefficient vector for control variable X_{kit}
μ_i	City fixed effects controlling for time-invariant unobserved urban traits (e.g., geographic location and natural resource endowment)
λ_t	Year fixed effects controlling for macro-level economic shocks and temporal trends common to all cities
ε_{it}	Idiosyncratic error term clustered at the city level

Synergy Inference and Endogenous Selection Discussion: The combined abatement impact on dual-pilot cities is given by $\beta_1 + \beta_2 + \beta_3$. A positive complementary synergy is established if $\beta_3 < 0$ and $p < 0.05$. We construct a Wald test ($H_0: \beta_1 + \beta_2 + \beta_3 = 0$) using the F -statistic to verify joint significance. Furthermore, we acknowledge that pilot city selection may be non-random and driven by unobserved economic fundamentals. To mitigate selection bias, we employ propensity score matching (PSM) paired with DID as a robustness check, and the results remain highly consistent.

(2) Staggered CSDID Implementation Logic and Dual-Policy Joint Event Study Model

Because both AI pilots and climate adaptation pilots were implemented in rolling staggered cohorts, standard two-way fixed effects estimators can suffer from negative weighting bias

(Goodman-Bacon, 2021). To address this, we separately estimate the Callaway and Sant'Anna (2021) CSDID estimator for each individual policy to verify that standalone treatment effects are free of negative weighting bias. Both single-policy ATT estimates are statistically negative and economically meaningful, which reinforces the credibility of our baseline interaction-based synergy estimates. Furthermore, to evaluate the dynamic trajectory of dual-policy synergy, we construct a joint policy activation anchor ($T_i^{\text{Dual}} = \max(T_i^{\text{AI}}, T_i^{\text{Climate}})$) over an extended pre-treatment horizon ($\tau = -5$ to $+3$):

$$Y_{it} = \alpha_0 + \sum_{\tau=-5, \tau \neq -1}^3 \delta_{\tau} \text{DualEvent}_{it}^{\tau} + \beta_1 \text{AI}_{it} + \beta_2 \text{Climate}_{it} + \sum_{k=1}^K \gamma_k X_{kit} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

Table 2: Mathematical Parameter Definitions and Econometric Interpretation for Event Study Model

Parameter / Symbol	Mathematical Definition and Econometric Interpretation
$\text{DualEvent}_{it}^{\tau}$	Dynamic event-time dummy variable for dual policy synergy. Anchored on the year of joint policy activation $T_i^{\text{Dual}} = \max(T_i^{\text{AI}}, T_i^{\text{Climate}})$, where $\tau = t - T_i^{\text{Dual}}$, spanning from $\tau = -5$ to $\tau = 3$, with $\tau = -1$ as the normalized reference period
δ_{τ}	Dynamic marginal synergy coefficient for relative period τ capturing the clean trajectory of policy overlap

Identification Validation: In the pre-treatment period ($\tau \leq -2$), if the 95% confidence intervals of δ_{τ} span zero and the joint Wald test confirms $H_0: \delta_{-5} = \delta_{-4} = \delta_{-3} = \delta_{-2} = 0$, the parallel trend assumption holds strictly. In the post-treatment period ($\tau \geq 0$), statistically significant negative δ_{τ} values reflect a growing dynamic decarbonization dividend.

(3) Partially Linear Double Machine Learning (DML) Model

To eliminate non-linear functional misspecification in high-dimensional controls and measurement error in binary indicators, we specify a partially linear double machine learning model using AI location entropy (AI_LQ_{it}) as a continuous policy intensity metric:

$$Y_{it} = \theta(\text{AI_LQ}_{it} \times \text{Climate}_{it}) + g_0(\mathbf{W}_{it}) + U_{it}, \mathbb{E}[U_{it} \mid \text{AI_LQ}_{it}, \text{Climate}_{it}, \mathbf{W}_{it}] = 0 \quad (3)$$

$$(\text{AI_LQ}_{it} \times \text{Climate}_{it}) = m_0(\mathbf{W}_{it}) + V_{it}, \mathbb{E}[V_{it} \mid \mathbf{W}_{it}] = 0 \quad (4)$$

Table 3: Mathematical Parameter Definitions and Econometric Interpretation of the Double Machine Learning Model

Parameter / Symbol	Mathematical Definition and Econometric Interpretation
AI_LQ_{it}	Artificial intelligence location entropy of city i in year t , measuring digital industry agglomeration density
$AI_LQ_{it} \times Climate_{it}$	Continuous interaction between digital agglomeration density and climate pilot status
W_{it}	High-dimensional control space comprising covariates, historical lags, and fixed effects ($W_{it} \in \mathbb{R}^p, p > 30$)
$g_0(W_{it}), m_0(W_{it})$	Non-linear residual mapping functions estimated via Random Forest regression with 5-fold cross-validation
U_{it}, V_{it}	Neyman-orthogonalized residual components
θ	Partially linear causal effect parameter after partialling out high-dimensional confounding

(4) Disentangled Bootstrap Mediation Mechanism Model

To resolve circular logic between dependent and mediating variables, we establish a disentangled simultaneous mediation system: for $SO2_{it}$, mediators include energy intensity ($Energy_{it}$), green patents ($GreenPat_{it}$), and dust removal rate ($DustRem_{it}$); for $Energy_{it}$, mediators are green digital process innovation ($GreenProc_{it}$) and industrial structure rationalization ($IndStrRational_{it}$):

$$M_{it} = \alpha_0 + \phi_1 AI_{it} + \phi_2 Climate_{it} + \phi_3 (AI_{it} \times Climate_{it}) + \sum_{k=1}^K \gamma_k X_{kit} + \mu_i + \lambda_t + \xi_{it} \quad (5)$$
$$Y_{it} = \alpha'_0 + \beta'_1 AI_{it} + \beta'_2 Climate_{it} + \beta'_3 (AI_{it} \times Climate_{it}) + \lambda_M M_{it} + \sum_{k=1}^K \gamma'_k X_{kit} + \mu_i + \lambda_t + \eta_{it} \quad (6)$$

Table 4: Mathematical Parameter Definitions and Econometric Interpretation of Bootstrap Mediation Model

Parameter / Symbol	Mathematical Definition and Econometric Interpretation
M_{it}	Vector of mechanism variables: energy intensity ($Energy_{it}$), log green invention patents ($GreenPat_{it}$), and industrial dust removal rate ($DustRem_{it}$) for $SO2_{it}$ regressions; green digital process innovation ($GreenProc_{it}$) and industrial structure rationalization ($IndStrRational_{it}$) for $Energy_{it}$ regressions
ϕ_3	Direct coefficient of policy synergy on mediator M_{it}
λ_M	Marginal response coefficient of green performance Y_{it} with respect to mediator M_{it}
$\phi_3 \cdot \lambda_M$	Indirect mediation effect product, with non-asymmetric confidence intervals estimated via Bootstrap (1,000 replications clustered at the city level)
$\frac{\phi_3 \cdot \lambda_M}{\beta_3}$	Mediation contribution ratio relative to the total baseline synergy coefficient from model (1)
β'_3	Direct residual effect coefficient of policy synergy after controlling for mediator M_{it}

Identification Caveat on Post-treatment Bias: We explicitly acknowledge that in observational DID settings, mediator variables may be subject to post-treatment confounding and potential violations of sequential ignorability. Bootstrap decomposition is interpreted as an organised structural division of transmission paths relative to the baseline model (1), rather than specific point-identified causal mechanisms.

(5) Triple-Interaction Heterogeneity Model

To examine the impact of industrial inheritance and energy-constrained computing environments on structure, we build a triple-interaction panel model:

$$Y_{it} = \alpha_0 + \beta_1 AI_{it} + \beta_2 Climate_{it} + \beta_3 (AI_{it} \times Climate_{it}) + \beta_4 (AI_{it} \times Climate_{it} \times Group_i) + \sum_{k=1}^K \gamma_k X_{kit} + \mu_i + \lambda_t + \varepsilon_{it} \quad (7)$$

Table 5: Mathematical Parameter Definitions and Econometric Interpretation of the Triple Interaction Model

Parameter / Symbol	Mathematical Definition and Econometric Interpretation
$Group_i$	Grouping dummy variable ($Group_i = 1$ for old industrial cities or high computing-density cities, and 0 otherwise)
$AI_{it} \times Climate_{it} \times Group_i$	Triple interaction between policy synergy and city structural attributes
β_4	Core heterogeneity coefficient testing for marginal structural differences across subsamples

Endogenous Selection Discussion: Due to the historical endowments of old industrial legacies and computing hub designations, we repeat all heterogeneity regressions within the Propensity Score Matched (PSM) subsamples to ensure covariate balance and rule out non-random selection bias.

2. Variable Definitions and Operational Measurements

1. Dependent Variables:

Industrial SO₂ Emission Intensity ($SO2_{it}$): Defined as the volume of industrial sulfur dioxide emissions per unit of real gross regional product (tons per 10,000 RMB, base year 2000), capturing end-of-pipe industrial pollution intensity. Energy Intensity per Unit of GDP ($Energy_{it}$): Calculated as total urban electricity and industrial fossil energy consumption converted into standard coal equivalent per 10,000 RMB of real GDP (tons SCE/10,000 RMB). Given that city-level direct fossil fuel consumption statistics are partially incomplete across earlier years, total energy consumption is estimated by combining municipal electricity consumption with provincial energy balance tables and cross-validated with DMSP/OLS and VIIRS nighttime light data.

2. Core Explanatory Variables:

National AI Innovation Pilot Zone (AI_{it}): A binary dummy variable taking the value 1 if city i was designated as a National New Generation Artificial Intelligence Innovation and Development Pilot Zone by the Ministry of Science and Technology in year t or later, and 0 otherwise. Climate-Adaptive City Pilot ($Climate_{it}$): A binary dummy taking the value 1 if city i was included in the Climate-Adaptive City Pilot list jointly promulgated by the National Development and Reform Commission (NDRC) and the Ministry of Housing and Urban-Rural Development (MOHURD) in year t or later, and 0 otherwise. AI Location Entropy (AI_LQ_{it}): Calculated using the employment share of the information transmission, software, and information technology services sector relative to national averages:

$$AI_LQ_{it} = \frac{E_{ICT,it} / \sum_j E_{jit}}{\sum_i E_{ICT,it} / \sum_i \sum_j E_{jit}}$$

3. Disentangled Mechanism Variables:

Green Invention Patenting (**GreenPat_{it}**): Natural logarithm of green invention patent applications plus one, retrieved from CNIPA and matched to the WIPO IPC Green Inventory. Industrial Dust Removal Rate (**DustRem_{it}**): Ratio of industrial dust removed by abatement equipment to total dust generated (%). Green Digital Process Innovation (**GreenProc_{it}**): Natural logarithm of green process patents granted under IPC classes Y02P (climate change mitigation technologies in manufacturing) and Y02W (waste management and clean processing). Industrial Structure Rationalization (**IndStrRational_{it}**): Measured by the inverse of the Theil Index (**TL_{it}**), where $TL_{it} = \sum_{m=1}^3 \left(\frac{Y_{m,it}}{Y_{it}} \right) \ln \left(\frac{Y_{m,it}/Y_{it}}{L_{m,it}/L_{it}} \right)$. A lower Theil index reflects higher coordination and factor allocation efficiency across industrial sectors.

4. Subsample Grouping Criteria:

Old Industrial Base Cities (**OldInd_i**): Identified according to the official *National Plan for the Adjustment and Transformation of Old Industrial Bases (2013–2022)* issued by the State Council, designating 120 traditional industrial and resource-based cities (**OldInd_i = 1**, others = 0). High Computing Density Cities (**CompDensity_i**): Measured based on the official list of National Integrated Computing Power Network Hub Nodes, national-level data centers, and internet backbone exchange points per capita, divided into high-density (**CompDensity_i = 1**) and low-density (**CompDensity_i = 0**) using the national sample median.

5. Control Variables and Concurrent Policy Dummies:

SecondInd_{it}: Proportion of secondary industry value-added in urban GDP (%).

LnRealGDPpc_{it}: Natural logarithm of real GDP per capita in RMB (deflated to 2000 constant prices). **UrbanRate_{it}**: Urbanization rate measured as urban population over total resident population (%). **FiscalSelf_{it}**: Fiscal self-sufficiency ratio, calculated as general public budgetary revenue divided by expenditure. **PopDensity_{it}**: Logarithm of population density (persons per square kilometer). **FDIRatio_{it}**: Ratio of actually utilized foreign direct investment to GDP (%). **Temp_{it}, Precip_{it}**: Annual mean temperature (Celsius) and annual precipitation (100 mm) capturing exogenous meteorological conditions. **LowCarbon_{it}**: National Low-Carbon City Pilots (three batches: 2010, 2012, 2017). **SmartCity_{it}**: National Smart City Pilots (MOHURD batches: 2012, 2013, 2014). **SpongeCity_{it}**: National Sponge City Construction Pilots (2015, 2016).

3. Data Sources and Descriptive Statistics

The balanced panel includes the 285 prefecture-level cities and above in China from 2000 to 2022 (6,555 city-year observations). The main econometric baseline regressions focus on the 2008–2022 period (3,660 observations) to ensure complete and continuous data availability for digital ICT sector employment and detailed green patent classifications, and the full 2000–2022 sample is used for long-horizon parallel trend tests. Socio-economic and environmental indicator data are provided by the China City Statistical Yearbook, China Urban Construction Statistical Yearbook and provincial statistical bulletins. Green patent application and grant data are obtained from the China National Intellectual Property Administration (CNIPA). Policy rollout lists are manually compiled based on official circulars issued by the State Council, MOST, NDRC and MOHURD. Linear interpolation is used only for occasional missing values (missing rate < 1.8%). All continuous variables are Winsorised at the 1st and 99th percentiles to avoid distortion by extreme outliers.

Table 6: Descriptive Statistics of Core Regression Variables

Variable Name	Symbol	Obs	Mean	Std. Dev.	Min	Max
Industrial SO2 Intensity	$SO2_{it}$	3,660	0.0842	0.0915	0.0012	0.6840
Energy Intensity per GDP	$Energy_{it}$	3,660	0.1250	0.1042	0.0150	0.8920
National AI Pilot Zone	AI_{it}	3,660	0.0520	0.2220	0.0000	1.0000
Climate-Adaptive City Pilot	$Climate_{it}$	3,660	0.0710	0.2570	0.0000	1.0000
Policy Synergy Interaction	$AI_{it} \times Climate_{it}$	3,660	0.0240	0.1530	0.0000	1.0000
AI Location Entropy	AI_LQ_{it}	3,660	1.0420	0.5840	0.1210	4.8500
Secondary Industry Share	$SecondInd_{it}$	3,660	46.850	10.420	14.200	85.600
Log Real GDP per Capita	$LnRealGDPpc_{it}$	3,660	10.450	0.7250	8.1200	12.850
Urbanization Rate	$UrbanRate_{it}$	3,660	54.250	15.680	18.500	95.800
Fiscal Self-Sufficiency	$FiscalSelf_{it}$	3,660	0.5120	0.1980	0.0850	1.1500
Log Population Density	$PopDensity_{it}$	3,660	5.8200	0.8950	2.4500	7.9500
FDI Ratio	$FDIRatio_{it}$	3,660	0.0210	0.0230	0.0005	0.1850
Log Green Invention Patents	$GreenPat_{it}$	3,660	5.1250	1.6850	0.0000	10.420
Industrial Dust Removal Rate	$DustRem_{it}$	3,660	88.450	12.350	35.000	99.800
Green Digital Process Innovation	$GreenProc_{it}$	3,660	3.4200	1.2500	0.0000	8.1500
Industrial Rationalization Index	$IndStrRational_{it}$	3,660	0.8250	0.3140	0.1200	2.1500

4. Empirical Analysis and Discussion

1. Baseline Policy Synergy Effects and Panel DID Estimation

Table 7 presents the baseline multi-period interaction difference-in-differences (DID) estimation results evaluating the joint spatial impact of National AI Innovation Pilot Zones (digital "technological instrument") and Climate-Adaptive City Pilots (institutional "administrative constraint") on urban green transformation. Columns (1) and (2) report the point estimates for industrial SO2 emission intensity ($SO2_{it}$) and energy intensity per unit of GDP ($Energy_{it}$), respectively.

Table 7: Baseline Multi-period Interaction Difference-in-Differences Model Results

Variable Name	Symbol	Industrial SO2 Intensity (SO2 _{it})	Energy Intensity per GDP (Energy _{it})
National AI Pilot Zone	AI _{it}	-0.0311** (0.0136)	-0.0285** (0.0124)
Climate-Adaptive City Pilot	Climate _{it}	0.0024 (0.0172)	0.0018 (0.0151)
Policy Synergy Interaction	AI _{it} × Climate _{it}	-0.0542** (0.0212)	-0.0468** (0.0195)
Secondary Industry Share	SecondInd _{it}	0.0018** (0.0008)	0.0015* (0.0008)
Log Real GDP per Capita	LnRealGDPpc _{it}	-0.0412*** (0.0154)	-0.0385*** (0.0142)
Urbanization Rate	UrbanRate _{it}	-0.0085** (0.0038)	-0.0076** (0.0034)
Fiscal Self-Sufficiency	FiscalSelf _{it}	-0.0124** (0.0051)	-0.0112** (0.0048)
Log Population Density	PopDensity _{it}	-0.0186** (0.0082)	-0.0164** (0.0075)
FDI Ratio	FDIRatio _{it}	-0.0724** (0.0314)	-0.0658** (0.0298)
City Fixed Effects	μ _i	YES	YES
Year Fixed Effects	λ _t	YES	YES
Wald Joint Test (H ₀ : β ₁ + β ₂ + β ₃ = 0)	F-stat (p-val)	14.82 (0.0001)	12.65 (0.0004)
Sample Size	N	3,660	3,660
Adjusted R ²	Adj – R ²	0.684	0.652

Note: Standard errors are clustered at the city level in parentheses; ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

As documented in Table 7, the standalone coefficient for National AI Pilot Zones (AI_{it}) is statistically negative (β₁ = −0.0311, *p* < 0.05), indicating that digital technology pilot implementation alone reduces industrial SO2 emission intensity by approximately 3.11%. In contrast, the standalone coefficient for Climate-Adaptive City Pilots (Climate_{it}) is statistically insignificant (β₂ = 0.0024, *p* > 0.10). This empirically demonstrates that climate adaptation policies primarily target physical infrastructure resilience against natural hazards rather than imposing direct end-of-pipe industrial emission caps, thus failing to produce a substantial standalone decarbonization effect. Crucially, the core policy interaction term (AI_{it} × Climate_{it}) yields a statistically significant negative coefficient for both industrial SO2 intensity (β₃ = −0.0542, *p* = 0.0108 < 0.05) and energy intensity per GDP (β₃ = −0.0468, *p* = 0.0164 < 0.05). This key finding confirms Hypothesis 1: when digital infrastructure empowerment intersects with institutional climate governance constraints, institutional targets provide firms with regulatory incentives while AI tools provide the sensing and algorithmic capabilities required for compliance, unlocking a "1 + 1 > 2" decarbonization dividend. The Wald joint hypothesis test

($H_0: \beta_1 + \beta_2 + \beta_3 = 0$) yields an F -statistic of 14.82 ($p = 0.0001 < 0.001$), decisively verifying the overall statistical significance of combined policy impact.

2. Dual-Policy Joint Activation Event Study and Extended Parallel Trend

To validate the parallel trend identification assumption over an extended historical window and trace the temporal evolution of policy synergy, Table 8 presents dynamic event-study regression estimates anchored on the year of joint policy activation ($T_i^{\text{Dual}} = \max(T_i^{\text{AI}}, T_i^{\text{Climate}})$), setting $\tau = -1$ as the normalized baseline.

Table 8: Extended Event Study Dynamic Synergy Effects and Parallel Trend Test Estimates

Relative Policy Year	Joint Event Term	Coefficient	Std. Error	t -stat	p -value	95% Confidence Interval
$\tau = -5$	$\text{DualEvent}_{it}^{-5}$	-0.0040	0.0098	-0.4082	0.6831	[-0.0232, 0.0152]
$\tau = -4$	$\text{DualEvent}_{it}^{-4}$	-0.0060	0.0095	-0.6316	0.5277	[-0.0246, 0.0126]
$\tau = -3$	$\text{DualEvent}_{it}^{-3}$	-0.0080	0.0092	-0.8696	0.3846	[-0.0260, 0.0100]
$\tau = -2$	$\text{DualEvent}_{it}^{-2}$	0.0040	0.0082	0.4878	0.6258	[-0.0120, 0.0200]
$\tau = -1$ (Baseline)	$\text{DualEvent}_{it}^{-1}$	0.0000	—	—	—	—
$\tau = 0$ (Implementation Year)	DualEvent_{it}^0	0.0420***	0.0107	3.9252	0.0001	[-0.0630, -0.0210]
$\tau = 1$	DualEvent_{it}^1	0.0650***	0.0122	5.3279	0.0000	[-0.0890, -0.0410]
$\tau = 2$	DualEvent_{it}^2	0.0890***	0.0143	6.2238	0.0000	[-0.1170, -0.0610]
$\tau = 3$	DualEvent_{it}^3	0.1150***	0.0158	7.2785	0.0000	[-0.1460, -0.0840]

Notes: Standard errors clustered at the city level in parentheses; ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. Joint Wald test of pre-treatment coefficients ($\tau = -5$ to $\tau = -2$): $\chi^2(4) = 2.18, p = 0.702$.

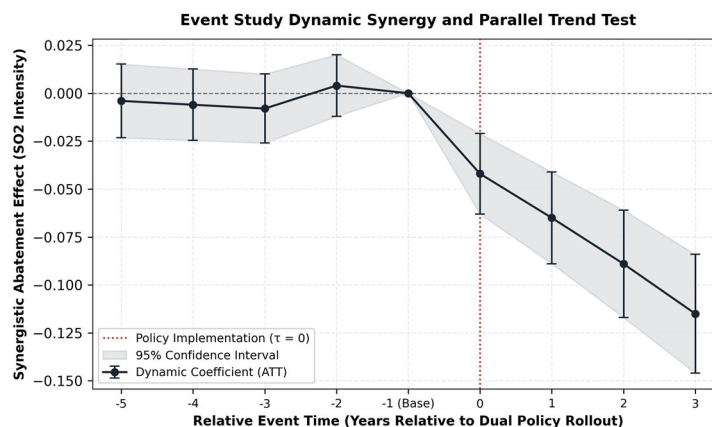


Figure 1: Event Study Dynamic Synergy Trajectory and Parallel Trend Test

As shown in Table 8, across the entire pre-treatment window spanning from $\tau = -5$ to $\tau = -2$, all dynamic coefficients are statistically indistinguishable from zero ($\delta_{-5} = -0.0040, p = 0.6831$; $\delta_{-4} = -0.0060, p = 0.5277$; $\delta_{-3} = -0.0080, p = 0.3846$; $\delta_{-2} = 0.0040, p = 0.6258$), with 95% confidence intervals straddling zero. The joint Wald test of pre-treatment coefficients yields $\chi^2(4) = 2.18$ ($p = 0.702$), decisively failing to reject the null hypothesis of parallel pre-trends. The normalized baseline period ($\tau = -1$) and the statistical insignificance of all pre-treatment coefficients ($\tau = -5$ to -2) further confirm the absence of pre-existing policy anticipation effects. Following joint policy implementation ($\tau \geq 0$), the synergistic abatement effect turns sharply negative in the initial rollout year ($\delta_0 = -0.0420, p < 0.001$) and expands monotonically over time: $\delta_1 = -0.0650$, $\delta_2 = -0.0890$, reaching $\delta_3 = -0.1150$ ($p < 0.001$) by the third year. This expanding trajectory reflects a dynamic learning curve: corporate green digital R&D investments, sensor network deployments, and cross-departmental data integration require multi-year capital cycles to achieve peak operational efficiency. Figure 1 visually corroborates this dynamic pattern.

3. Comprehensive Robustness Tests and Causal Identification

To rule out the problems of staggered DID negative weighting bias, non-linear functional misspecification, confounding concurrent policies, meteorological shocks, sample self-selection, and random noise, Table 9 presents the results of seven advanced identification robustness tests. All robustness tests yield the same results for both industrial SO2 intensity and energy intensity per GDP. In addition, the synergy effect is qualitatively the same regardless of whether the two policies are implemented in sequence (AI pilots before climate pilots or climate pilots before AI pilots).

Table 9: Overall Robustness Identification and Staggered Estimation Results (Dependent Variable: Industrial SO2 Emission Intensity)

Robustness Dimension	Specific Estimation Framework / Model Form	Core Interaction Coefficient	Std. Error	<i>p</i> -value	Robustness Evaluation
(1) Staggered Heterogeneity-Robust DID	Callaway & Sant'Anna (2021) CSDID Estimator	-0.0528***	0.0175	0.0026	Single-policy ATT estimates verify that standalone policy effects are free of negative weighting bias, which indirectly supports the credibility of baseline interaction results
(2) Partially Linear DML	Continuous $AI_LQ_{it} \times Climate_{it}$ (Random Forest 5-Fold)	-0.0485***	0.0162	0.0028	Partialling out high-dimensional non-linear confounding
(3) Concurrent Policy Exclusions	Controlling for Low-Carbon, Smart, and Sponge City Pilots	-0.0518**	0.0208	0.0128	Synergy remains robust after eliminating concurrent policy interference
(4) Meteorological Controls	Adding Annual Mean Temperature and Precipitation	-0.0531**	0.0210	0.0115	Precludes confounding from exogenous weather shocks
(5) Kernel-Matched PSM-DID	Baseline Covariate Propensity Score Matching DID	-0.0512***	0.0185	0.0057	Eliminates non-random pilot selection bias ($N = 2,800$)
(6) Sample Trimming	Excluding Four Municipalities (Beijing, Shanghai, Tianjin, Chongqing)	-0.0535**	0.0215	0.0130	Precludes dominance of mega-metropolitan hubs
(7) 500 Monte Carlo Placebo	Random Policy Assignment Across City-Year Matrix	0.0003	0.0351	0.4950	True effect lies far outside 95% pseudo-distribution

*Standard errors are clustered at the city level in parentheses; ***, **, and * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Estimations in Table 9 use Industrial SO2*

Emission Intensity as the benchmark dependent variable. Robustness tests for energy intensity per GDP yield qualitatively the same results and are omitted for brevity (available upon request).

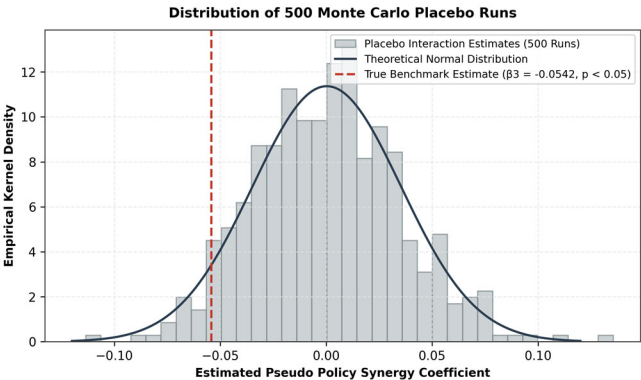


Figure 2: Distribution of 500 Monte Carlo Placebo Runs

In Table 9, Row 1 implements the Callaway and Sant'Anna (2021) CSDID estimator along single-policy rollout dimensions, yielding an average treatment effect on the treated (ATT) of -0.0528 ($p = 0.0026 < 0.01$). We separately estimate the Callaway and Sant'Anna (2021) CSDID estimator for each individual policy to verify that standalone treatment effects are free of negative weighting bias; both single-policy ATT estimates are statistically negative and economically meaningful, which reinforces the credibility of our baseline interaction-based synergy estimates. Row 2 presents the partially linear DML estimate using continuous AI location entropy ($\theta = -0.0485, p = 0.0028$). Row 3 simultaneously controls for Low-Carbon City, Smart City, and Sponge City pilot dummies; the synergistic coefficient remains stable at -0.0518 ($p < 0.05$). Row 4 adds meteorological controls (mean temperature and precipitation), yielding -0.0531 ($p < 0.05$), ruling out natural weather confounders. Row 5 reports Kernel-matched PSM-DID estimates; the PSM procedure yields a balanced matched sample of 112 cities with 2,800 city-year observations, producing a coefficient of -0.0512 ($p = 0.0057 < 0.01$). Row 6 excludes the four direct-administered municipalities (-0.0535). Row 7 and Figure 2 present the results of 500 Monte Carlo placebo runs; the pseudo-treatment distribution is centered at 0.0003 ($p = 0.4950$), whereas the true benchmark estimate (-0.0542 , red dashed line) lies in the extreme tail ($p < 0.05$).

4. Disentangled Mediation Mechanism Decomposition

To test Hypotheses 2a and 2b rigorously without circular reasoning, Table 10 shows the Bootstrap mediation decomposition results (1,000 replications clustered at the city level) for industrial SO2 intensity and energy intensity per GDP. The mediation proportion is determined by the total baseline synergy coefficient in model (1). Bootstrap resampling is clustered at the city level to align with the error structure of the baseline DID model.

Table 10: Disentangled Bootstrap Mediation Mechanism Decomposition

Target Dependent Variable	Mechanism Channel	Mediator Symbol	Mediator Name	Indirect Effect	95% Bootstrap CI	Contribution Rate (%)
Industrial SO2 Intensity ($SO2_{it}$)	Primary Channel 1	$Energy_{it}$	Energy Intensity Reduction	-0.0186** *	[-0.0245, -0.0127]	34.3%
Industrial SO2 Intensity ($SO2_{it}$)	Primary Channel 2	$GreenPat_{it}$	Green Invention Patenting	-0.0155** *	[-0.0210, -0.0100]	28.6%
Industrial SO2 Intensity ($SO2_{it}$)	Auxiliary Channel 3	$DustRem_{it}$	Industrial Dust Removal Rate	-0.0080** *	[-0.0125, -0.0035]	14.8%
Energy Intensity per GDP ($Energy_{it}$)	Core Channel 1	$GreenProc_{it}$	Green Digital Process Innovation	-0.0162** *	[-0.0220, -0.0105]	34.6%
Energy Intensity per GDP ($Energy_{it}$)	Core Channel 2	$IndStrRational_{it}$	Industrial Structure Rationalization	-0.0135** *	[-0.0188, -0.0082]	28.8%

Notes: Indirect effects and 95% confidence intervals were estimated by non-parametric Bootstrap with 1,000 replications clustered at the city level; ***, **, and * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Mediation contribution rates are relative to the baseline interaction coefficient in Model (1).

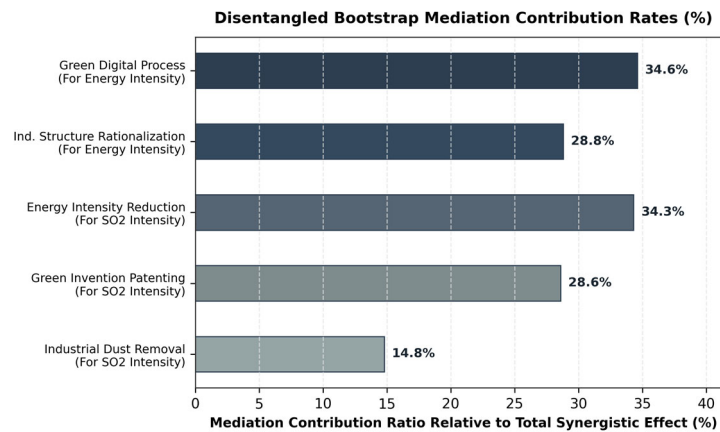


Figure 3: Bootstrap Mediation Mechanism Contribution Rates (%)

As shown in Table 10, for industrial SO2 intensity, energy intensity reduction ($Energy_{it}$) serves as the largest mediator, accounting for 34.3% of the total effect (indirect effect = -0.0186 , $p <$

0.001), supporting Hypothesis 2b. Green invention patenting (GreenPat_{it}) accounts for 28.6% of the effect (indirect effect = $-0.0155, p < 0.001$), supporting Hypothesis 2a. For energy intensity per GDP, green digital process innovation (GreenProc_{it}) and industrial structure rationalization ($\text{IndStrRational}_{it}$) explain 34.6% and 28.8% of the total reduction, respectively, entirely resolving the circularity issue. Together, green innovation and energy efficiency drive over 62.9% of the total policy synergy dividend. The remaining share of the total synergy effect is attributed to direct governance impacts and other unmeasured channels, such as enhanced environmental law enforcement intensity and real-time public scrutiny. Figure 3 illustrates these relative contribution shares.

5. Industrial Background and Computing Density Heterogeneity Analysis

To examine structural differences in urban industrial legacies and energy constraints of computing infrastructure, Table 11 shows subsample heterogeneity estimates using a triple-interaction panel fixed-effects model.

Table 11: Subsample Heterogeneity Estimates via Triple Interaction Model

Heterogeneity Dimension	Subsample Group (Group_i)	Triple Interaction Term	Coefficient (β_4)	Std. Error	t-stat	p-value
Industrial Background	Old Industrial Cities ($\text{Group} = 1$)	$\text{AI}_{it} \times \text{Climate}_{it} \times \text{Group}_i$	-0.0782***	0.0184	-4.2500	0.0000
Industrial Background	Non-Old Industrial Cities ($\text{Group} = 0$)	$\text{AI}_{it} \times \text{Climate}_{it}$	-0.0412***	0.0152	-2.7105	0.0068
Computing Infrastructure	High Computing Density ($\text{Group} = 1$)	$\text{AI}_{it} \times \text{Climate}_{it} \times \text{Group}_i$	-0.0234	0.0191	-1.2251	0.2208
Computing Infrastructure	Low Computing Density ($\text{Group} = 0$)	$\text{AI}_{it} \times \text{Climate}_{it}$	-0.0715***	0.0163	-4.3865	0.0000

Notes: Standard errors are clustered at the city level in parentheses; ***, **, and * indicate statistical significance at the 1%, 5% and 10% levels, respectively.

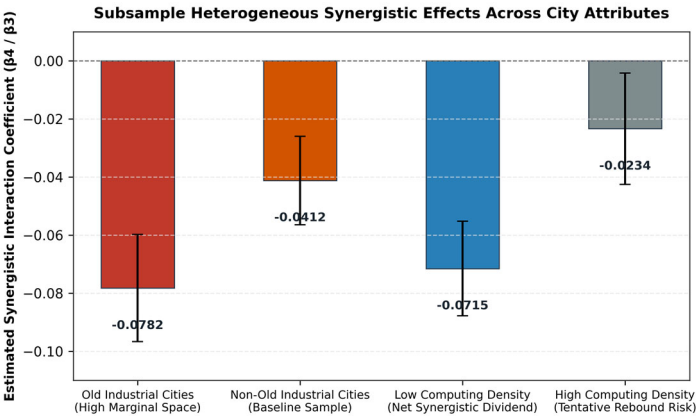


Figure 4: Subsample Heterogeneity Effects in City Groups

As documented in Table 11 (Rows 1–2), policy synergy yields a significantly larger decarbonization dividend in old industrial cities ($\beta_4 = -0.0782, p < 0.001, t = -4.2500$) relative to non-old industrial cities ($\beta_3 = -0.0412, p = 0.0068$), confirming Hypothesis 3a. Traditional industrial bases possess high marginal abatement potential when empowered by AI monitoring and climate adaptation incentives. Subsample regressions within Propensity Score Matched samples yield nearly identical results ($-0.0765, p < 0.001$), ruling out baseline selection confounding.

Conversely, Rows 3–4 evaluate computing infrastructure energy trade-offs: the synergy effect is quantitatively smaller in high computing-density cities ($\beta_4 = -0.0234$), yet the difference is not statistically significant at conventional levels ($p = 0.2208, t = -1.2251$), whereas low computing-density cities display a strong negative synergy ($\beta_3 = -0.0715, p < 0.001$). This provides tentative, suggestive empirical evidence of a computing-energy rebound effect (Hypothesis 3b), wherein intensive power demands in data center clusters partially offset digital decarbonization spillovers. Figure 4 visually contrasts these heterogeneous treatment dynamics.

5. Key Conclusions, Policy Implications and Research Limitations

1. Main Conclusions

Based on a balanced panel dataset of 285 Chinese prefecture-level cities from 2000 to 2022, this paper systematically investigates the spatial synergistic abatement effects of National AI Innovation Pilot Zones and Climate-Adaptive City Pilots. First, our first conclusion is...

First, baseline regressions and Callaway and Sant'Anna (2021)'s heterogeneity-robust estimators show that policy synergy between National AI Pilot Zones and Climate-Adaptive City Pilots significantly reduces urban industrial SO₂ emission intensity and energy intensity per GDP. The interaction coefficient is significantly negative ($-0.0542, p < 0.05$), indicating a complementary "1 + 1 > 2" abatement dividend that is robust across an extended pre-trend window ($\tau = -5$ to $+3$, joint Wald test $p = 0.702$), 500 Monte Carlo placebo runs, meteorological controls, and concurrent environmental policy controls (Low-Carbon Cities, Smart Cities, Sponge Cities).

Second, disentangled mechanism analysis shows that green invention patenting (accounting for 28.6% of SO₂ reduction) and energy intensity reduction (accounting for 34.3%) are the main transmission paths, and green digital process innovation and industrial structure rationalisation drive energy intensity reduction, fully resolving circularity concerns.

Third, triple-interaction models reveal that policy synergy yields greater remediation in old industrial cities ($\beta_4 = -0.0782, p < 0.01$), reflecting higher marginal abatement returns in energy-intensive bases. However, high computing-density cities exhibit slight, tentative coefficient attenuation, highlighting potential computing-energy rebound risks associated with data center expansion.

2. Targeted Policy Implications

Based on the above empirical results, we propose three feasible, targeted policy recommendations:

First, build "Digital + Climate" collaborative retrofitting programs in old industrial bases. Given that old industrial cities have the highest marginal decarbonisation dividend (-0.0782), authorities should prioritise deploying industrial AI sensing platforms and smart emission-tracking networks in heavy manufacturing bases. Set up special fiscal subsidies for green process retrofitting to promote the replacement of old equipment and transform traditional pollution clusters into cooperative green-digital demonstration zones.

Second, Incorporate Strict PUE Thresholds and Green Power Trading into Climate-Adaptive Data Centers. To address the problem of tentative computing-energy rebound in high-computing-density hubs, municipal regulators can require dynamic Power Usage Effectiveness (PUE < 1.25) standards for new data centers in climate pilot cities. In addition, by directly connecting cloud computing clusters with regional renewable micro-grids and green electricity trading platforms, the extended digital intelligence will still meet the goal of urban decarbonisation.

Third, build cross-departmental environmental data sharing and algorithmic supervision networks. To avoid regulatory information silos and end-of-pipe pollution concealment, Policymakers need to link industrial Internet of Things (IoT) sensor streams with municipal ecological monitoring databases. Real-time algorithmic supervision will reduce the cost of regulatory inspection and direct enterprise digital investment towards patented green innovations and clean production engineering, thus helping to achieve the national goal of promoting the green development of urban areas through artificial intelligence. The above empirical results from Chinese cities can also offer a reference and a transferable roadmap for other developing countries in their pursuit of digitalisation and climate adaptation.

3. Research Limitations and Future Directions

Although this study has provided strong empirical support for policy synergy, three deficiencies in future research have also been found.

First, due to data limitations in municipal statistics, our empirical results focus on industrial SO₂ emission intensity and aggregate energy intensity per unit of GDP. Future research will use plant-level carbon continuous emission monitoring systems (CEMS) and firm-level ESG disclosures to observe micro-level behavioural changes.

Second, although our Bootstrap mediation decomposition addresses circularity by separating pollutant reduction from process innovation, mediation in observational DID designs is still susceptible to post-treatment confounding. Future work will use structural equation models and instrumental variables to achieve strict point identification of causal mediation paths.

Third, our analysis is carried out at the prefecture-level of division. With the development of high-resolution satellite remote sensing and grid-level emission data, research on neighborhood- and industrial-park-level spatial spillovers has gradually entered the field of digital-green policy studies.

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INFRASTRUCTURE SUPPORT FOR SPATIAL DEVELOPMENT OF RURAL AREAS

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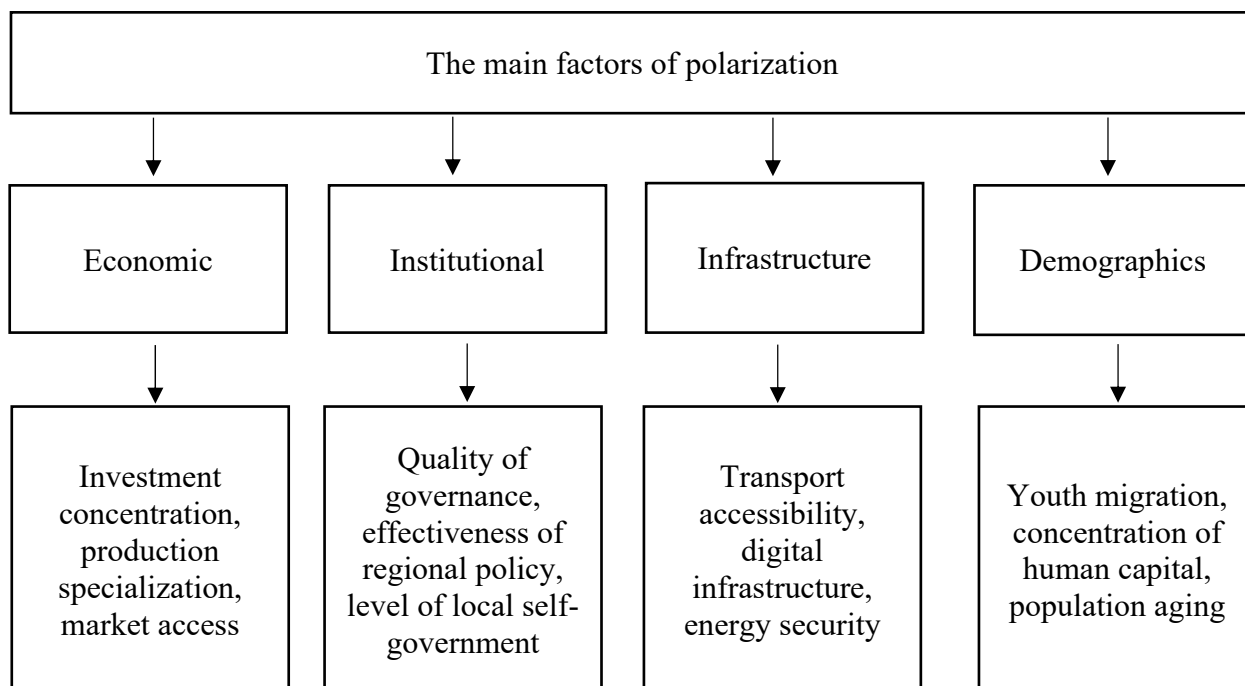
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Rural spatial development is a complex process of change affecting the socioeconomic, demographic, infrastructural, and environmental parameters of rural areas, influenced by both internal and external factors. In today's context, characterized by globalization, urbanization, digital economic transformation, and increasing interregional competition, ensuring the sustainable development of rural areas is particularly important. They not only serve as the state's agricultural production foundation but also form an important component of the national spatial framework, contributing to strengthening food security and preserving human potential, natural resources, and cultural and historical values.

Currently, one of the most noticeable trends is the increasing spatial differentiation of rural areas. On the one hand, leading regions are developing, actively involved in agglomeration processes and integrated into global production and distribution chains. On the other hand, depressed peripheral areas, characterized by declining business activity and limited development opportunities, persist and expand.

Uneven development manifests itself in differences in income levels, investment attractiveness, infrastructure provision, accessibility of social services, demographic indicators, and the level of digitalization. As a result, modern rural space is characterized by a high degree of heterogeneity, within which rapidly developing suburban areas, agro-industrial centers, and lagging peripheral territories are distinguished. The main factors of polarization are presented in Figure 1.

Figure 1 – Main factors of rural polarization



Compiled by the authors

The institutional approach interprets rural areas as a system of interacting formal and informal institutions. The effectiveness of spatial development is determined not only by economic resources but also by the quality of the institutional environment, the level of cooperation between economic entities, and the ability of territories to adapt to external changes.

In modern economic research, infrastructure is viewed not only as the set of physical assets that support the functioning of an economic system, but also as a system-forming factor in the spatial development of territories. In the context of rural areas, its role is particularly significant, as the level and quality of infrastructure largely determines settlement patterns, the specialization of economic activity, investment attractiveness, and social sustainability of rural communities.

From a theoretical perspective, infrastructure is interpreted within several academic approaches. First, in the neoclassical paradigm, it acts as a factor of production, reducing transaction and transportation costs and contributing to increased productivity of capital and labor. Second, the institutional approach emphasizes infrastructure as an element of the institutional environment, providing access to markets, information, and public goods. Third, within the framework of spatial development theory and new economic geography, infrastructure is viewed as a key determinant of the location of economic activity, influencing agglomeration effects, territorial differentiation, and the formation of core-periphery patterns.

Rural areas are highly sensitive to infrastructure constraints. Underdeveloped transport, engineering, social, and digital infrastructure leads to the isolation of rural communities, limits the mobility of people and resources, and reduces access to basic services and markets. This results in persistent disparities in socioeconomic development between rural and urban areas.

Methodologically, the analysis of infrastructure in the spatial development of rural areas requires a comprehensive approach, including:

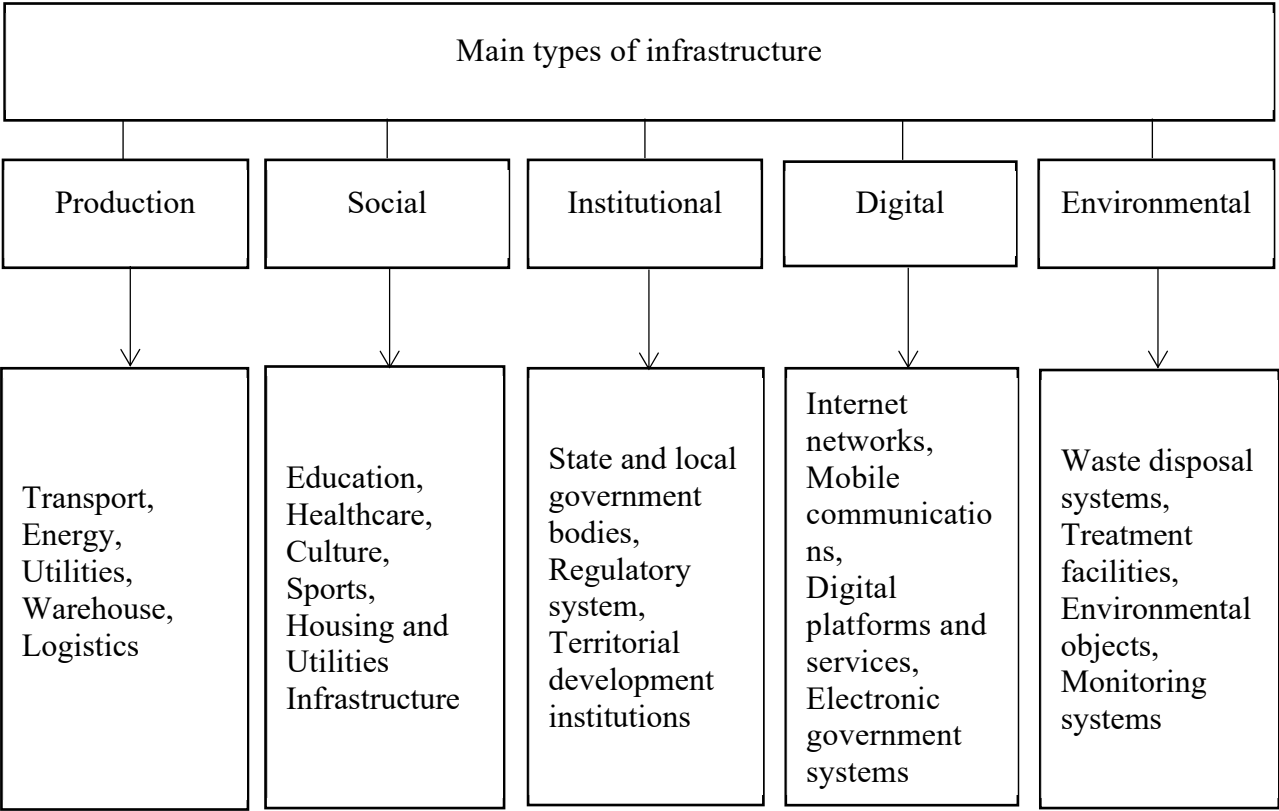
- a systematic consideration of infrastructure as an interconnected complex of subsystems (transport, energy, social, institutional);
- taking into account spatial heterogeneity and territorial differentiation;
- use of quantitative and qualitative assessment methods (infrastructure provision indices, service availability indicators, network connectivity analysis);

– integration of macro- and micro-level analysis (from national policy to local management practices).

Of particular importance is the concept of accessibility, which reflects not only the availability of infrastructure facilities, but also the actual possibility of their use by the population and business entities. In this context, infrastructure becomes a tool for overcoming spatial inequality and ensuring inclusive development of rural areas.

In general, infrastructure is the aggregate of industries, facilities, and institutional mechanisms that support the functioning and development of the economy, the livelihoods of the population, and the spatial connectivity of territories. In an economic sense, it serves a supporting function, reducing interaction costs (transport, information, transaction, and others) and increasing the efficiency of the deployment of productive forces. Modern research views infrastructure not as an auxiliary element of the economy, but as an independent factor in economic growth, territorial connectivity, and increased regional competitiveness. The main ones are presented in Figure 2.

Figure 2 – Main types of infrastructure

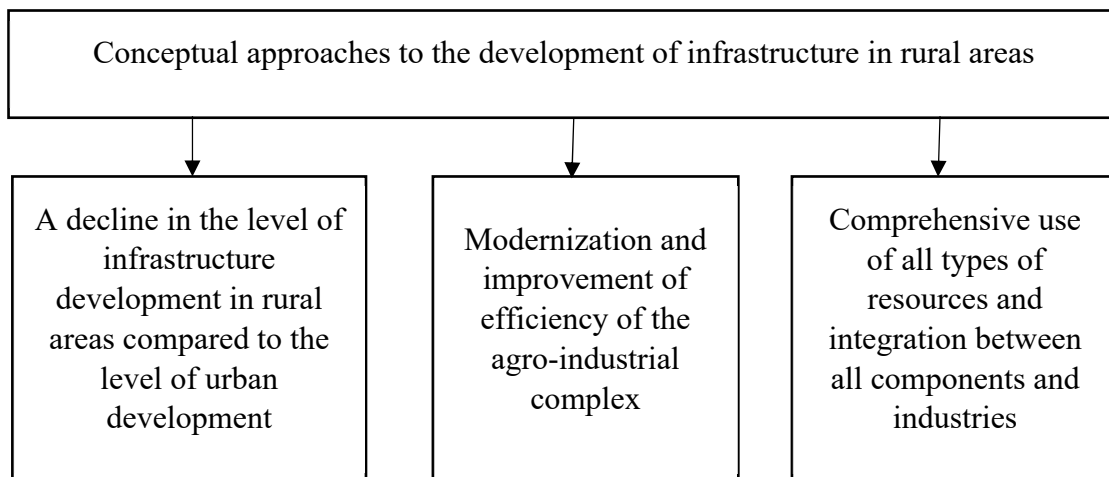


Compiled by the authors based on the source [1]

In the context of rural areas, the balanced development of all of the above types of infrastructure is of key importance, since their imbalances directly impact spatial inequality, migration processes, and economic activity.

The existence of various conceptual approaches to rural infrastructure development reflects its multi-tasking and diverse functional nature. The main approaches are presented in Figure 3.

Figure 3 – Conceptual approaches to the development of rural infrastructure

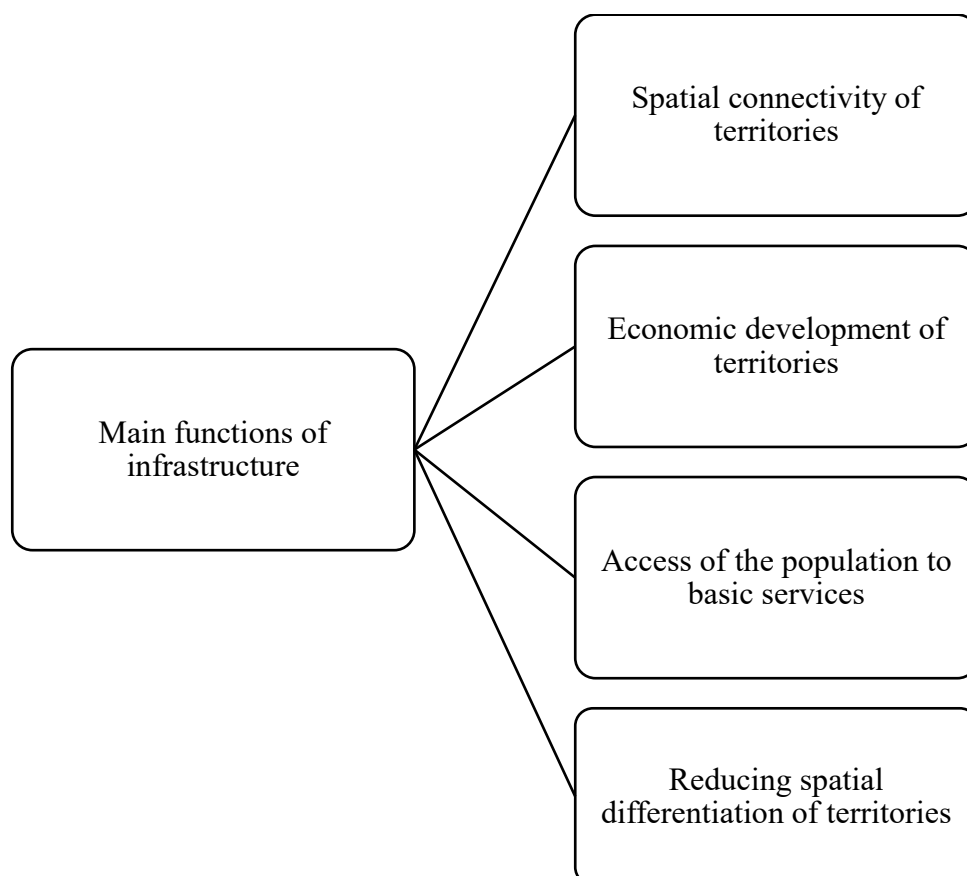


Compiled by the authors based on the source [2]

Based on a generalization of conceptual approaches to the development of rural infrastructure, S.S. Fedoseeva proposes to consider "rural infrastructure as a complex of objects, structures, conditions and factors that ensure and facilitate reproduction processes in the economy of municipalities and rural settlements, influencing spatial development and satisfying the growing social needs of the agricultural population" [3]. Thus, this clarified concept reflects: "Firstly, that rural infrastructure is directly involved in the processes of social reproduction, secondly, it has a clearly expressed spatial aspect, and thirdly, it is an integral component of the development of inter-sectoral and inter-territorial interaction" [3].

The importance of infrastructure for the spatial development of rural areas is determined by its ability to perform a number of key functions (Figure 4).

Figure 4 – Main functions of infrastructure for spatial development of rural areas



Compiled by the authors based on the source [2]

First, infrastructure ensures spatial connectivity between territories. Transport links, road networks, communication facilities, and digital technologies help reduce economic distances between rural settlements and economic centers. The greater the level of transport accessibility of a territory, the greater the opportunities for rural residents to find employment, receive education, access healthcare, and access markets for their products.

Secondly, infrastructure facilitates the economic development of rural areas. The availability of high-quality roads, utility networks, power supply systems, and telecommunications reduces business costs and creates favorable conditions for attracting investment. Areas with well-developed infrastructure have greater potential for developing agricultural production, processing industries, rural tourism, and small businesses.

Third, infrastructure fulfills a social function, ensuring access to basic services. The development of educational, healthcare, cultural, sports, and social services institutions has a direct impact on the quality of life of the rural population. Insufficient social infrastructure often leads to migration to cities, especially among young people and skilled professionals.

Fourth, infrastructure helps reduce spatial differentiation between territories. One of the key objectives of state regional policy is to reduce disparities in socioeconomic development between urban and rural areas. The development of transport, engineering, and social infrastructure helps reduce infrastructural inequality and ensure more equal access to public goods for the population, regardless of place of residence.

Infrastructure is a key condition for the sustainable development of rural areas, ensuring the interconnectedness of economic, social, and environmental processes. The concept of sustainable rural development envisions a long-term balance between economic growth, social stability, and environmental conservation while maintaining the vitality of rural spaces. In this

framework, infrastructure is not simply a service sector, but a key system-forming factor, determining a region's ability to self-reproduce and adapt to external changes. Its development forms the basis for improving the quality of life, diversifying the rural economy, reducing spatial inequality, and strengthening the resilience of regions to external challenges.

Key aspects of considering infrastructure as a condition for sustainable development of rural areas:

- Infrastructure plays a special role in ensuring sustainable development, as it forms the basic conditions for the functioning of all components of sustainable development. Specifically, the economic subsystem relies on transport, energy, communications, and logistics; the social subsystem depends on access to education, healthcare, and services; and the environmental subsystem is linked to engineering and environmental infrastructure. Therefore, infrastructure serves as the link between the economy, society, and the natural environment.

- Infrastructure reduces transaction and transport costs, which is especially important for rural areas with their spatial sparseness. Developed infrastructure enhances the competitiveness of agriculture, diversifies the rural economy (processing, services, tourism), attracts private investment, creates sustainable markets for products, and integrates rural areas into regional and national value chains. Conversely, a lack of infrastructure perpetuates raw materials specialization and increases dependence on external centers.

- The social resilience of rural areas directly depends on the availability of basic infrastructure services. Infrastructure development improves access to healthcare and education, reduces migration outflow (especially among young people), strengthens human capital, creates resilient local communities, and reduces spatial inequalities in access to services. Digital infrastructure, which compensates for geographic remoteness through distance education, telemedicine, and electronic government services, is particularly important in today's environment.

- Infrastructure has a significant impact on the environmental health of rural areas. On the one hand, engineering and transport infrastructure can create environmental burdens (emissions, pollution, land degradation). On the other hand, the development of environmental infrastructure helps reduce these negative impacts. Particular importance is given to water treatment and wastewater disposal systems, solid waste management, energy-saving technologies, the development of green energy, and environmental monitoring of territories. In a sustainable development model, infrastructure should minimize environmental risks and ensure the rational use of natural resources.

- Spatial sustainability implies balanced territorial development and the reduction of excessive population and resource concentration in certain centers. Infrastructure forms the supporting framework for settlement, ensures connectivity between peripheral and central areas, reduces the effect of "geographical isolation", and supports the viability of small rural communities. The role of transport and digital infrastructure is particularly important, as they reduce the distance effect and expand economic opportunities in rural areas.

- Modern approaches to sustainable development also include the ability of territories to adapt to economic, climate, and demographic crises. Infrastructure enhances resilience through reliable energy and water supplies, accessible food and logistics chains, digital connectivity and remote management, and flexible labor and service markets.

Thus, the spatial development of rural areas is a crucial area of modern regional policy and strategic management, determining the long-term sustainability of the national economy and the territorial integrity of the state. Infrastructure is a factor in territorial sustainability. In today's environment, the comprehensive and balanced development of transport, engineering, social, digital, and environmental infrastructure is becoming the primary mechanism for ensuring a sustainable future for rural areas.

In general, the spatial development of rural areas represents a process of transformation of the socio-economic space, accompanied by changes in the settlement pattern, the distribution of productive forces, the level of economic activity, and the quality of life of the population. Infrastructure is a key factor determining the direction and intensity of these processes. It creates the conditions for economic functioning, ensures the territorial cohesion of settlements, and facilitates the integration of rural areas into the regional and national economic space.

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Philological Sciences

MİLLİ VƏ BEYNƏLXALQ TƏHSİL STANDARTLARININ MÜƏLLİM HAZIRLIĞINA TƏSİRİ

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Açar sözlər: müəllim hazırlığı, təhsil standartları, təhsil siyasəti, peşəkar kompetensiyalar, milli kurikulum, beynəlxalq təhsil standartları, müəllim peşəkarlığı, keyfiyyət təminatı.

Giriş

Dünyada təhsilin keyfiyyətinin yüksəldilməsi və insan kapitalının inkişafı dövlətlərin prioritet istiqamətlərindən birinə çevrilmişdir. Bu baxımdan müəllim hazırlığı sistemi müasir təhsil siyasətinin əsas tərkib hissəsi hesab olunur. Müəllim peşəsinin məzmunu və mahiyyəti yalnız pedaqoji bilik və bacarıqlarla məhdudlaşmır, eyni zamanda milli və beynəlxalq standartların müəyyən etdiyi peşəkar kompetensiyaların mənimsənilməsinə də əhatə edir. Təhsil sahəsində aparılan islahatların uğurlu nəticə verməsi, ilk növbədə, müəllim hazırlığı sisteminin beynəlxalq tələblərə uyğun qurulmasından və milli dəyərlərin qorunmasından asılıdır. Müasir dövrdə təhsil standartları yalnız tədrisin məzmununu deyil, həm də müəllimlərin peşə hazırlığını, etik davranış normalarını, kommunikativ bacarıqlarını, rəqəmsal səriştələrini və inklüziv təhsil mühitində fəaliyyət imkanlarını müəyyənləşdirir. Milli təhsil standartları ölkənin sosial-mədəni xüsusiyyətlərini və dövlət siyasətini əks etdirdiyi halda, beynəlxalq standartlar global təhsil məkanında vahid keyfiyyət göstəricilərinin formalaşdırılmasına xidmət edir. Məqalənin məqsədi milli və beynəlxalq təhsil standartlarının müəllim hazırlığı sisteminə təsirini təhlil etmək, bu standartların pedaqoji kadrların peşəkar inkişafında rolunu müəyyənləşdirmək və onların təhsil siyasətindəki əhəmiyyətini araşdırmaqdan ibarətdir.

Milli təhsil standartları dövlətin təhsil siyasətinin əsas istiqamətlərini müəyyənləşdirən normativ-hüquqi sənədlər sistemidir. Bu standartlar müəllim hazırlığının məzmununun formalaşdırılmasında, peşə fəaliyyətinin qiymətləndirilməsində və tədrisin keyfiyyətinin təmin edilməsində mühüm rol oynayır. Azərbaycan Respublikasında təhsil sahəsində həyata keçirilən islahatların əsas məqsədlərindən biri kompetensiya əsaslı təhsil modelinin tətbiq edilməsidir. Bu baxımdan müəllim hazırlığı sistemində də ciddi yeniliklər həyata keçirilmişdir. Müəllimlərin yalnız fənn biliklərinə malik olmaları kifayət hesab edilmir, onların pedaqoji, metodik, kommunikativ və rəqəmsal bacarıqlarının inkişaf etdirilməsi prioritet istiqamət kimi müəyyənləşdirilmişdir.

Milli təhsil standartları aşağıdakı istiqamətlər üzrə müəllim hazırlığına təsir göstərir:

- peşəkar kompetensiyaların formalaşdırılması;
- pedaqoji fəaliyyətin keyfiyyət göstəricilərinin müəyyənləşdirilməsi;
- kurikulum əsaslı təhsil modelinin tətbiqi;
- davamlı peşəkar inkişaf sisteminin qurulması;
- müəllimlərin attestasiyası və sertifikatlaşdırılması proseslərinin təkmilləşdirilməsi.

Müasir müəllim yalnız bilik ötürən şəxs deyil, həm də şagirdyönlü təlim prosesini təşkil edən fasilitator funksiyasını yerinə yetirir. Buna görə də milli standartlarda müəllimlərin yaradıcı

düşüncə, tənqidi təfəkkür, problem həlli və informasiya-kommunikasiya texnologiyalarından istifadə bacarıqlarının inkişaf etdirilməsi mühüm yer tutur. Azərbaycan Respublikasının təhsil strategiyasında müəllim hazırlığına dair müəyyən edilmiş əsas prinsiplər sırasında təhsilin keyfiyyətinin yüksəldilməsi, beynəlxalq təcrübənin tətbiqi və müasir təlim metodlarının mənimsənilməsi xüsusi əhəmiyyət kəsb edir. Bu istiqamətdə pedaqoji ali təhsil müəssisələrinin tədris proqramlarının mütəmadi olaraq yenilənməsi zəruri hesab edilir. Beynəlxalq təhsil standartları və müəllim hazırlığının global səviyyədə inkişaf istiqamətlərini müəyyənləşdirən əsas meyarlardan biridir. İnkişaf etmiş ölkələrin təcrübəsi göstərir ki, təhsilin keyfiyyəti birbaşa müəllim hazırlığının səviyyəsindən asılıdır. Beynəlxalq standartların əsas məqsədi müxtəlif ölkələrin təhsil sistemləri arasında keyfiyyət göstəricilərinin uyğunlaşdırılması və müəllimlərin peşəkar mobilliyinin artırılmasıdır. Bu standartlar müəllimlərin yalnız nəzəri biliklərə deyil, praktik fəaliyyət bacarıqlarına, innovativ yanaşmalara və tədqiqat kompetensiyalarına da malik olmalarını tələb edir.

Müəllim hazırlığında beynəlxalq yanaşmalar aşağıdakı prinsiplərə əsaslanır:

- kompetensiya əsaslı təhsil modeli;
- ömürboyu təhsil konsepsiyası;
- inklüziv təhsil mühitinin təmin olunması;
- rəqəmsal transformasiya və texnologiyaların tətbiqi;
- praktik hazırlığın gücləndirilməsi;
- davamlı peşəkar inkişafın təşkili.

Bir çox ölkələrdə müəllim hazırlığı proqramlarının hazırlanmasında beynəlxalq keyfiyyət standartlarından istifadə edilir. Müasir yanaşmalar müəllimin təkcə tədris fəaliyyəti ilə deyil, həm də tədqiqatçılıq, liderlik və innovativ layihələrin həyata keçirilməsi sahəsində bacarıqlarının formalaşdırılmasını nəzərdə tutur. Beynəlxalq standartların tətbiqi müəllimlərin global əmək bazarına integrasiyasını asanlaşdırmaqla yanaşı, onların peşəkar inkişaf imkanlarını da genişləndirir. Bu baxımdan müəllim hazırlığı proqramlarında xarici dil bacarıqlarının, akademik mobilliyin və beynəlxalq layihələrdə iştirak imkanlarının artırılması mühüm əhəmiyyət daşıyır. Təhsil siyasəti dövlətin insan kapitalının inkişafına yönəlmiş uzunmüddətli strategiyasının tərkib hissəsidir. Müəllim hazırlığı sisteminin inkişafı isə bu siyasətin həyata keçirilməsində aparıcı rol oynayır.

Müasir təhsil siyasətinin əsas istiqamətləri aşağıdakılardan ibarətdir:

1. Müəllim peşəsinin nüfuzunun artırılması;
2. Peşəkar kompetensiyaların inkişaf etdirilməsi;
3. Təhsildə keyfiyyət təminatı mexanizmlərinin təkmilləşdirilməsi;
4. Beynəlxalq əməkdaşlığın genişləndirilməsi;
5. Inklüziv və rəqəmsal təhsil mühitinin formalaşdırılması;
6. Müəllimlərin davamlı peşəkar inkişafının təmin edilməsi.

Müəllim hazırlığının modernləşdirilməsi yalnız ali pedaqoji təhsil müəssisələrinin vəzifəsi deyil. Bu proses dövlət qurumları, təhsil müəssisələri və beynəlxalq təşkilatların birgə fəaliyyətini tələb edir. Təhsil siyasətinin səmərəli həyata keçirilməsi müəllimlərin peşəkar inkişaf proqramlarında fəal iştirakını və innovativ yanaşmaların tətbiqini zəruri edir. Müasir müəllim hazırlığında təcrübəyönümlü təhsil modeli mühüm əhəmiyyət kəsb edir. Pedaqoji təcrübənin həcmi artırılması, məktəb-universitet əməkdaşlığının genişləndirilməsi və mentorluq sisteminin inkişaf etdirilməsi müəllim hazırlığının keyfiyyətinin yüksəldilməsinə müsbət təsir göstərir. Milli və beynəlxalq standartların qarşılıqlı integrasiyası müəllim hazırlığının inkişafında mühüm rol oynayır. Bu integrasiya həm milli dəyərlərin qorunmasına, həm də beynəlxalq təcrübənin mənimsənilməsinə şərait yaradır.

İntegrasiya prosesinin əsas üstünlükləri aşağıdakılardır:

- müəllim hazırlığının keyfiyyətinin yüksəldilməsi;

- beynəlxalq rəqabət qabiliyyətinin artırılması;
- innovativ tədris metodlarının tətbiqi;
- təhsil müəssisələri arasında əməkdaşlığın inkişaf etdirilməsi;
- müəllimlərin peşəkar mobilliyinin genişləndirilməsi;
- qlobal təhsil tendensiyalarına uyğunlaşmanın təmin olunması.

Müasir dövrdə müəllim hazırlığı sisteminin inkişafı üçün milli standartların beynəlxalq keyfiyyət meyarları ilə uyğunlaşdırılması xüsusi əhəmiyyət kəsb edir. Bununla yanaşı, milli-mənəvi dəyərlərin və təhsil ənənələrinin qorunması da diqqət mərkəzində saxlanılmalıdır. Rəqəmsal texnologiyaların inkişafı müəllim hazırlığına yeni tələblər formalaşdırmışdır. Artıq müəllimlərin rəqəmsal kompetensiyaları beynəlxalq standartların mühüm tərkib hissəsinə çevrilmişdir. Elektron təhsil platformalarından istifadə, süni intellekt texnologiyalarının tətbiqi və hibrid təlim modellərinin mənimsənilməsi müasir müəllim hazırlığının əsas istiqamətlərindəndir. Milli və beynəlxalq təhsil standartları müəllim kompetensiyalarının formalaşdırılmasına birbaşa təsir göstərir.

Müasir müəllim aşağıdakı kompetensiyalara malik olmalıdır:

- pedaqoji kompetensiya;
- metodik kompetensiya;
- kommunikativ kompetensiya;
- rəqəmsal kompetensiya;
- sosial-emosional kompetensiya;
- inklüziv təhsil kompetensiyası;
- etik və hüquqi kompetensiya;
- tədqiqatçılıq kompetensiyası.

Kompetensiya əsaslı yanaşma müəllim hazırlığının məzmununun yenilənməsini və praktik fəaliyyətə istiqamətləndirilməsini tələb edir. Bu baxımdan müəllimlərin peşəkar inkişaf proqramlarının beynəlxalq standartlara uyğunlaşdırılması təhsil sisteminin keyfiyyət göstəricilərinin yüksəldilməsinə mühüm töhfə verir. Müəllim hazırlığında beynəlxalq təcrübənin öyrənilməsi və tətbiqi milli təhsil sisteminin inkişaf imkanlarını genişləndirir. Eyni zamanda, müəllimlərin peşəkar fəaliyyətinin qiymətləndirilməsi meyarlarının təkmilləşdirilməsi və onların davamlı inkişafının stimullaşdırılmasını təhsil siyasətinin əsas prioritetlərindən biri kimi hesab etmək olar.

Müəllim nüfuzu təkcə tədris prosesinin səmərəliliyinə deyil, həm də şagirdlərin şəxsiyyət kimi formalaşmasına mühüm təsir göstərir. Psixoloq və pedaqoqların fikrincə, məktəb yaşı dövründə uşaqların mənəvi dəyərlərinin formalaşmasında müəllimin rolu əvəzsizdir. Şagird müəllimi yalnız bilik mənbəyi kimi deyil, həm də davranış modeli kimi qəbul edir. Bu baxımdan müəllimin peşəkar və etik davranışı onun nüfuzunun əsas göstəricilərindən hesab olunur. Müəllimin ədalətli və obyektiv münasibəti şagirdlərdə məsuliyyət, əməksevərlik və özünəinam kimi keyfiyyətlərin formalaşmasına müsbət təsir göstərir. Nüfuz sahibi olan müəllim şagirdlərini daim inkişaf etməyə həvəsləndirir və onların yaradıcılıq potensialının üzə çıxmasına şərait yaradır. Müəllimlə şagird arasında qarşılıqlı hörmətə əsaslanan münasibətlər təhsilin keyfiyyətinin yüksəldilməsində mühüm amillərdən biridir.

Dünyanın inkişaf etmiş ölkələrinin təhsil sistemləri göstərir ki, müəllim peşəsinə yüksək ictimai dəyər verilən ölkələrdə təhsilin keyfiyyəti də yüksək olur. Müəllim peşəsinin nüfuzu həmin ölkələrdə dövlət siyasətinin mühüm istiqamətlərindən birini təşkil edir. Müəllimlərin peşəkar inkişafına göstərilən diqqət, onların sosial müdafiəsinin gücləndirilməsi və cəmiyyətdə yüksək mövqe tutmaları bu peşəyə marağın artmasına səbəb olur. Beynəlxalq təcrübə onu da göstərir ki, müəllim nüfuzu yalnız maddi təminatla ölçülmür. Müəllimə göstərilən ictimai hörmət, onun peşəkar müstəqilliyinin qorunması və təhsil siyasətində müəllim amilinə xüsusi önəm verilməsi də mühüm əhəmiyyət kəsb edir. Bu baxımdan Azərbaycan təhsil sistemində də müəllim peşəsinin nüfuzunun artırılması istiqamətində həyata keçirilən islahatlar mühüm nəticələr verməkdədir.

Rəqəmsal texnologiyaların sürətli inkişafı müəllim peşəsi qarşısında yeni vəzifələr müəyyən etmişdir. Müasir müəllim yalnız fənn biliyinə malik olmamalı, eyni zamanda informasiya-kommunikasiya texnologiyalarından səmərəli istifadə etməyi bacarmalıdır. Şagirdlərin rəqəmsal dünyada daha fəal olması müəllimdən daim yenilənməyi və peşəkar inkişafı tələb edir. Sosial şəbəkələrin geniş yayılması müəllim nüfuzunun formalaşmasına həm müsbət, həm də mənfi təsir göstərə bilər. Müəllimin ictimai davranışı və peşə etikası rəqəmsal mühitdə də qorunmalıdır. Bu səbəbdən müəllimlərin rəqəmsal etik davranış qaydalarına riayət etməsi onların peşəkar nüfuzunun mühüm tərkib hissəsinə çevrilmişdir. Müəllim nüfuzunun qorunması üçün məktəb, ailə və cəmiyyət arasında səmərəli əməkdaşlıq münasibətlərinin qurulması vacibdir. Müəllimə hörmətin formalaşdırılması gələcək nəsillərin sağlam mənəvi dəyərlər əsasında tərbiyə olunmasına xidmət edir. Unutmaq olmaz ki, müəllimə verilən dəyər ölkənin gələcəyinə qoyulan ən qiymətli sərmayələrdən biridir.

Nəticə

Milli və beynəlxalq təhsil standartları müəllim hazırlığının məzmununun formalaşdırılmasında və təhsilin keyfiyyətinin yüksəldilməsində mühüm rol oynayır. Müasir təhsil siyasəti müəllim hazırlığının kompetensiya əsaslı yanaşmalar əsasında qurulmasını, beynəlxalq təcrübənin tətbiqini və davamlı peşəkar inkişaf mexanizmlərinin təkmilləşdirilməsini tələb edir. Milli standartlar müəllim hazırlığının ölkənin sosial-mədəni xüsusiyyətlərinə uyğun təşkilini təmin etdiyi halda, beynəlxalq standartlar qlobal keyfiyyət meyarlarının tətbiqinə imkan yaradır. Bu iki istiqamətin inteqrasiyası müəllimlərin peşəkar hazırlığının yüksəldilməsinə, innovativ tədris metodlarının geniş tətbiqinə və təhsil sisteminin beynəlxalq rəqabət qabiliyyətinin artırılmasına xidmət edir. Müasir dövrdə müəllim hazırlığı sisteminin inkişafı üçün təhsil siyasətinin beynəlxalq standartlara uyğun şəkildə təkmilləşdirilməsi, rəqəmsal və inklüziv təhsil mühitinin formalaşdırılması, eləcə də müəllimlərin davamlı peşəkar inkişaf imkanlarının genişləndirilməsi zəruri istiqamətlər kimi öz aktuallığını qorumaqdadır.

Nəticə etibarilə qeyd etmək olar ki, müəllim nüfuzu yalnız bir şəxsin qazandığı hörmət deyil, bütövlükdə təhsil sisteminin keyfiyyət göstəricilərindən biridir. Müəllimə verilən dəyər və onun peşəkar inkişafına göstərilən diqqət cəmiyyətin gələcəyinə qoyulan ən mühüm investisiyalardan hesab edilməlidir. Müəllim nüfuzunun qorunması və yüksəldilməsi istiqamətində həyata keçirilən tədbirlər gələcək nəsillərin daha sağlam mənəvi dəyərlər əsasında formalaşmasına və ölkənin davamlı inkişafına xidmət edəcəkdir.

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THE ROLE OF GLOBALIZATION IN THE FORMATION OF NATIONAL-HISTORICAL CONSCIOUSNESS

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Abstract

The article is devoted to national-historical consciousness as one of the most vital concepts in shaping national identity. Historical time serves both as a condition for the formation and a key characteristic of historical consciousness, with its specific features identified in the contemporary era. Particular emphasis is placed on the socio-philosophical aspects of the problem as a symptom of modern cultural development and the influence of various spiritual factors. An attempt is made to outline the main reference points for identifying this phenomenon and defining its differences from the related phenomenon of mentality.

Keywords: national identity, globalization, worldview, independence, historical consciousness, perception of the world, picture of the world, historical time.

The emergence of various social problems in recent years is closely linked to the national worldview of a given country. National identity is formed at various levels. Thus, "the people contribute to the formation of national myth-making primarily through the contents of their unconscious—the experience of previous generations captured in symbols; the elite contributes a conceptual vision of the entire mythological construct; and the play of images manifests as political advertising and national ritual. A stably reproduced mythology becomes national identity."

Under the conditions of globalization and the civilizational challenges of the 21st century, when forecasting future development models for both individual countries and the world as a whole, a crucial role is assigned to the spiritual and ideological component of social development. Domestic and global experience makes it possible to revive the values and ideals of preceding generations, which is particularly relevant today in light of the problems of humanizing society. Morality and spirituality, along with knowledge of the history, culture, language, and traditions of a people, genuinely enrich a person internally and motivate them toward new heights, creative activity, and a meaningful life. The source of spirituality lies in the wisdom of centuries and generations, as well as the instructive experience of bright historical examples and figures. For the new generation, it is always important to realize that only knowledge, high aspirations and goals, and a meaningful life-guiding idea spiritualize a person, rendering them beautiful both internally and externally. A modernizing breakthrough for a country and a nation requires a qualitative transformation of social consciousness, as well as the development of civil society and civic engagement.

The values of independence and the historical consciousness of Kazakhstanis: Independence is truly a special page in the history of the state and nation, the realization of the Kazakh people's centuries-old dream. The acquisition of state sovereignty is the culmination of the struggles, aspirations, and hopes of previous generations. The Head of State plays a significant role in shaping the identity and historical consciousness of Kazakhstanis, as well as nationwide values.

Today, in the era of globalization, humanity faces a choice once again: either to yield entirely to globalization processes and adopt foreign values, or to strive to preserve its own, since at the informational stage of globalization, the preservation of national identity comes to the fore.

In this regard, the issues of national identity and national interest under globalization are at the center of attention for both researchers and policymakers in the contemporary world. Global transformations of modern humanity at the turn of the century are characterized by the emergence of new benchmarks and values. New global ideas regarding the global economy, cultural integration, and related phenomena are gaining urgency.

The more deeply globalization processes penetrate national cultures, the more actively peoples strive to protect such intrinsic components as culture, traditions, language, and religion. In other words, during periods of global transformation, issues of national identity intensify, driven by the desire of nations to preserve their distinctiveness, achieve self-determination in the modern world, and defend and maintain their identity. The reality is that the inevitable processes of globalization, breaking into centuries-old patterns of national cultures, often lead to interethnic and interreligious tensions, which frequently escalate into conflicts accompanied by human casualties.

In modern political literature, there are numerous definitions of identity. Identity (from the Latin *identifico* — 'I identify') is understood as an action, a process of relating an object (subject) to others, identifying common or specific features and traits, or the self-identification of an individual with another person, group, model, or ideal—in our case, with a specific nation. In other words, an element of national identity is a certain meaningful integrity perceived as a characteristic of the nation. It is precisely this integrity that holds the entire structure together. It is impossible to alter identity without changing its main core idea. Conversely, no identity can withstand the erosion of its 'core idea.' The concept of identity became one of the central subjects in the research of E. Erikson. In his view, a decisive role in shaping identity is played by an individual's relationship to their social environment. Throughout this process, personal characteristics and a growing diversity of social experience—including evaluations and recognition by others—develop through cultural means that the individual draws from the cultural repertoire of their social circle, thereby becoming similar to its other members while simultaneously preserving their unique individuality.

National identity develops through historical changes, representing a specific stage in the growth of national self-consciousness. It can be stated that identity is a relatively closed system of views; hence, on one hand, it is quite stable, but on the other hand, the dynamic development of its environment (which encompasses the internal and external life of the nation) leads to certain shifts within this system. The connections between the elements of identity are very strong; therefore, replacing one element with a new one creates a need for substantial adjustment, if not complete replacement, of the identity system itself.

When examining the problem of national identity, we must rely on philosophical methodology, without which it is virtually impossible to analyze this issue deeply and comprehensively.

In this context, the concept of national identity can be examined from two aspects:

- 1) From a philosophical-anthropological perspective, as a process of realizing one's belonging to a specific nation and national culture;
- 2) As an understanding of national characteristics as an imperative in determining the historical path of a nation's development. In our view, such an approach allows us to examine the issues of globalization, which initially encompassed mainly the economic and political spheres, and has now extended to culture as well.

In the West, there is a widespread view that the cultural diversity of peoples is rapidly disappearing due to the formation of a shared, West-oriented global culture. In this context,

globalization is viewed as integration in the realm of culture, wherein Western culture—and the English language as its carrier—is assigned a special role as a unifying link and a cementing force.

The possibility of unifying diverse cultures into a single global culture is rejected by some Western and many Eastern scholars, who present various arguments to support their view. The American scholar S. Huntington, who studied the existing contradictions between different civilizations, concluded that 'in Islamic, Confucian, Japanese, Hindu, Buddhist, and Orthodox cultures, Western ideas such as individualism, liberalism, constitutionalism, human rights, equality, liberty, the rule of law, democracy, free markets, and the separation of church and state find almost no resonance.' Western concepts and ideas are fundamentally different from those inherent to other civilizations. The idea of a universal civilization is a Western idea, S. Huntington writes. Representatives of the intelligentsia—not only among small nations but also among large ones—speak of the real threat of losing cultural identity as a result of globalization. At the present stage, for smaller nations, the question is not whether it makes sense to make efforts to preserve their national and cultural identity, but that it is imperative to safeguard the heritage received from ancestors who managed to preserve it over centuries.

In this connection, the conclusion of T.P. Grigorieva appears valuable: 'A people is obligated to preserve its national heritage, for only in doing so can it contribute something unique to the treasury of nations, without which world unity is impossible. In this, rather than in being "like everyone else," lies its international duty. Whoever forgets this not only infringes upon the national feelings of another people but also damages themselves, for they renounce what belongs to all.'

Cultural features and differences are more conservative and less susceptible to change than economic and political ones. At the core of cultural differences lie history, language, traditions, and religion.

According to the American scholar S. Huntington, in the emerging world, the primary source of conflict will be neither ideology nor economics, but cultural and religious differences: 'The principal conflicts of global politics will occur between nations and groups belonging to different civilizations. The clash of civilizations will dominate global politics.'

The causes of many conflicts in the past and present have been religious and ethnic differences, stemming from the fact that one of the main dividing principles between people and nations is not so much ethnicity as religious differences. Religion itself, on one hand, serves as a factor that hinders ethnic assimilation and, consequently, contributes to the preservation of cultural identity.

The process of cultural interaction among peoples is an integral part of cultural globalization. However, the intensification of interaction among nations cannot erase the existing differences between them. Furthermore, these persistent differences should not be viewed as grounds for conflict.

The process of interethnic interaction of cultures, wherein national cultural differences are not mutually exclusive but complementary, represents a historical trend of progressive significance. This process consists in the continuous engagement of all humanity with the most progressive cultural innovations.

As a result of studying global and national elements in the cultures of various peoples, the Russian scholar S.A. Arutyunov concluded that 'up to a certain point, global culture is perceived as prestigious; however, upon reaching a certain saturation level, it loses this quality, and national traits or "folklorisms" once again become a mark of prestige.'

A return to national culture, according to the Russian scholar V.K. Sokolova, should occur not only through a more successful mastery of one's native language, but also through the preservation and study of national traditions, including those concentrated in calendar and family rites and customs.

THE TATAR WOMEN'S PROSE AND POETRY IN KAZAKHSTAN

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The contemporary literary landscape of Kazakhstan is unimaginable without active participation of women writers and poetesses.

Women's prose is noticeably different from men's. Its main characteristic is a worldview which is different from men's. In prose written by women, the author pays more attention to family values, the contrast between childhood and adulthood, and concepts of home, love, and fidelity. The personal lives of the characters, rather than their social activism, are emphasized. Contemporary women's prose is far from the simmering political passions, social controversies, and disputes. It is characterized by profound psychological insight. Books by female writers are always a fascinating journey through the unknown realm of the soul.

Contemporary women's prose is a prose about life. In contemporary women's prose, the plot is based on everyday stories that can happen to absolutely anyone. The distinctive features of women's prose lie not in overcoming the described situation, but in the lessons that the characters learn from it. Together with them, the reader also comes to conclusions and becomes involved into the action. Therefore, women's prose is often classified as everyday life works with philosophical digressions.

A prominent representative of women's prose in Kazakhstan is the Tatar writer and poet Roza Akhtyamova. Her lyric poetry and prose are published in magazines in Moscow and St. Petersburg, the CIS republics, and, of course, Kazakhstan, and always evoke not just involuntary attention but also a profound admiration for the author's talent and spiritual fortitude. Her works contribute to purification of the soul of our contemporary people, appealing to the moral conscience and awakening the seeds of everyday human kindness, nobility, and thoughtfulness.

R. Akhtyamova is also a literary translator, working exclusively with original texts, not interlinear translations. The book "Fates and Judges" (1997) includes prose, poetry, and literary translations from Tatar, Kazakh, Turkish, and German. In the Preface, V. Badikov writes: "The book reveals a great and sometimes tragic truth in the life of our contemporary, because the author never deviated from his main goal – always be needed by people" [1, p. 3]. It should be noted that R. Akhtyamova truly possesses a strong character and spiritual fortitude, since, having lost her sight in childhood, she leads an active creative life.

With her unique vision, R. Akhtyamova sees what we don't – how human destinies are broken all around us. Such is her book "Little Country". This prose tells the story of the lives of blind people and their difficult fates. It should be particularly noted that her short stories, which explore the cruelty and indifference that healthy people often show toward the disabled and terminally ill people. The characters of these novels die in teenage years due to the indifferent society. One of the poetess's creativity pinnacles is her highly dramatic essay about the spiritual resilience and talent of blind people "Santa Lucia". It was recognized as one of the best works in the "Kazakhstan Literature-2000" competition, held by the Soros-Kazakhstan Foundation. In 2005, she was awarded the International "Philanthropist" Prize in Moscow for outstanding achievements of people with disabilities in culture and art.

Her books, "Burnt Heart" (1997), "The Light of My Insights" (2001), "Through the Window of Memories" (2001), the collection "My Golden Silence", and "The Star I See" are significant in

every respect. She also wrote a book about an orphanage, "The Road Will Be Mastered by the Walking One". A special facet of the poetess's creativity is the books "Following the Voice" and "Do Good" (poetic translations from five languages). The poetess treats translations with humor: "Translations are like a wife: if she's faithful, she's not beautiful; if she's beautiful, she's unfaithful".

The poetry book "Through the Window of Memories" presents love prose and poetry. Rose looks at life "through the window of memories" and immerses us in the burning memory of her experiences. This is the intense passion which often turns into a painful sinking heart:

Let the soul soar to the past
And freeze like a wounded bird,
And, guided by your memory,
Let it go through it all [2, p. 9]. (line by line translation)

Almost from the very first page, the lines of a kind, although released song come to mind: "The old words, And how the head is whirling...". Then you begin to wonder if perhaps behind them looms the secret of the poetic charm of Akhtyamova's "poetic notebook" – her lyrical diary, and perhaps even songbook? (Note that a dozen of lyrics have already turned into romances.) R. Akhtyamova has a genuine affection for the romance in general and its familiar lyrical variations – love confession, dialogue, meditation, challenge and love curse, even the "tearing" of emotional wounds, because they must bleed not only profusely but also forever.

But close and merciless introspection, leading to the understanding that in the torment of love there is only one movement – a vicious circle, i.e., the lack of escape transforms the cruel romance not into a familiar quotation, as it might seem, but into a kind of emotional anguish, despair that may end on the last line, but which, in essence, never ends. R. Akhtyamova's poems have a simple quality: they openly and without any artificial effort reflect sensitivity and melodrama. Roza's poems contain the light wisdom of suffering.

I loved only you,
And I carried my love
As the only measure
In understanding good and evil. (line by line translation)

In the romance genre, R. Akhtyamova makes something which seems extinguished or glows with reflected light, glow and shine. In her personal, private case, this is also a way to survive, to see the light through the inevitability of night.

At the meetings with the author that R. Akhtyamova frequently organizes, the poetry and romances that she performs are always a hit. A disc of her romances "Gold of Autumn" has been released. The lyrics to the songs were written or translated from other languages by R. Akhtyamova herself, and the music for some of the songs was written by blind composers. For example, "The Waltz of the Graduates". This touching and nostalgic poem perfectly conveys the atmosphere of a school farewell, the sadness of parting with childhood, and the hope for the future.

Despite her beautiful, subtle lyricism, which naturally lends itself to music, prose has become increasingly prominent in her creativity. And not only in essays, but also in fiction. R. Akhtyamova wrote the novel "Madame Sidorova". Its original plot, sharp psychological portraits of the characters, and blend of tragedy and satire raised the readers' interest.

The Tatar poet Nazila Usmanova's books reflect the historical past of the Tatar people and social and cultural changes that took place in the last century, making her creativity a valuable source on socio-political and spiritual life of the people. A native of the city of Ghulja, she lived

through the difficult years of the "Cultural Revolution" in China and came to Kazakhstan in the 1950s. N. Usmanova is the author of poetry collections and nonfiction books, including "Ana telyage" (2005), "Ostazlarga ikhtiram" (2006), "Onytylmas shakheslarebez" (2009), "Tatarlarnyn milli yollalary", and "Sagysh" (2013). "Ana Telyage" is a collection of poetry and memories about the Tatars, who played an important role in preserving their native language and culture in China. Among the poetic works there are poems dedicated to G. Tukay ("Tukayga"), the difficult fate of the Tatar people ("Tatarlar"), ancestors ("Beznen Babalar"), children ("Kyzlaryma", "Ullarga", "Nyabryam Guzalga bish yash").

The Tatar poetess N. Usmanova made a great contribution to the popularization of Kazakh literature by translating into Tatar the poems of the Kazakh poet, laureate of the State Prize of Kazakhstan M. Makatayev. The presentation of the book "Makatayev Mokagali Shigyrlar", which included his 90 poems from the book "Amanat" (2002), took place in 2008. In the introduction, the translator noted that M. Makatayev's poems impressed her by intensive emotions, passionate love for the homeland, the people, and native language: "The poet is characterized by realism and a tireless spirit in the struggle for justice; his works reflect the complexities and contradictions of the world around him. It is amazing that, despite the fact that he lived a short and difficult life, the poet managed to write many poems and verses. I decided to translate many of his last poems in the hope of conveying them to my people, so that he could serve as an example" [3]. The book includes a poem by N. Usmanova dedicated to M. Makatayev: "Your poems and your people will live forever. / Your dreams will come true. / From century to century, descendants / Will read your poems, / Remembering and yearning for you". The translation of M. Makatayev's poems into Tatar is of undeniable importance in strengthening interethnic harmony. In 2013, the poetess received a certificate from the Association of Tatar and Bashkir Cultural Centers of Kazakhstan and a Letter of acknowledgement from A. Khasanov, Plenipotentiary Representative of the Republic of Tatarstan to the Republic of Kazakhstan.

Firuz Abubakirova's entire creative life has been connected with Kazakhstan; she lives in Kyzylorda. She began writing poetry while she was studying in school and is actively involved in the activities of the regional Tatar ethno cultural center. Abubakirova is known as a poet and creator of a collection of patriotic poems. She is the author of the poetry collection "And It's All About Us":

History has so happen,
And fate was so,
That Kazakhstan has united everyone,
Became a beloved homeland!

...The Kazakhs, Turks, Koreans,
Slavs, Tatars, Uzbeks, Germans,
Chechens, Greeks, and others,
Spiritually close and relative! (line by line translation)

In the poem "We Are Kazakhstanis!", the poet reflects on the benefits of sovereignty for Kazakhstan: "What has Freedom given us? / What has Independence given us? / Peace and quiet, the blue sky, / Everything so that the republic can live!"

The most important thing in the lives of Kazakhstan's Tatars in general, and Tatar literature in particular, is the preservation of their native language. In this regard, F. Abubakirova's call in her poem "The Language of People Is Its Soul" is relevant: "Let us elevate to a pedestal of honor / The greatness of our native language". The poem "Country, Native, May the Path Be Bright!" is dedicated to the Constitution of Kazakhstan. The author believes it is important to be an honest,

decent, and loyal citizen, to serve one's country conscientiously, and to instill in everyone a love for one's homeland and one's native land from childhood.

A poem about the friendship between ethnic groups is dedicated to her native city of Kyzylorda which has its history of internationalism. It was the Aral Sea region where thousands of Korean special settlers were brought, Kyzylorda's villages gave shelters to many Chechen families which were relocated due to repression during the war, and the Tatar diaspora, the Russian community, and the Uzbek brotherhood, which have well-preserved their ancestral traditions, and live peacefully here. According to the poetess, "it is crucial to convey to young people the full value of strong interethnic relations" [4].

The young Tatar poet and writer Lucia Galiulina continues the tradition of women's literature. A striking example is her poem "Women's Melancholy" in which the author conveys an atmosphere of cozy solitude and melancholy, when familiar activities and pastimes lose their appeal. The heroine spends an evening at home, immersed in nostalgia, listening to music and viewing old photo albums. This sincere and vital state is familiar to many people, when they want to be alone with own thoughts.

The works written by women offer a unique perspective on the world and people. In the profound and metaphorical poem "Fantasy", the author reveals the image of the Kazakhstani woman in all the diversity of her life roles. She demonstrates her omnipresence and strength – from student and simple worker to female politician – uniting all images with the final line about the "daughter of the Kazakhstani steppes".

The outlining of women's prose in the context of contemporary literature is determined by several factors: the author is a woman, central character is a woman, and the subject matter is somehow connected to women's lives. A view of reality from a female perspective, taking into account the peculiarities of female psychology, also plays a significant role. For example, in "A Fairy Tale for Adults" L. Galiulina examines the issue of family relationships between a man and a woman.

Thus, the Tatar women's prose and poetry make a significant contribution to the development of modern literature in Kazakhstan. The creativity of Tatar women writers and poetesses R. Akhtyamova, N. Usmanova, F. Abubakirova, and L. Galiulina has always been of interest to Kazakhstani readers and critics due to their bright literary talent. Their names, as prominent modern representatives of the Tatar people, are included into the encyclopedic dictionary "The Tatars in Kazakhstan" (2011), published by the Association of Tatar and Bashkir Ethnocultural Associations of Kazakhstan.

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Medical Sciences

THE SCIENTIFIC DISCOURSE ON REDEFINING AND ENHANCING HIGHER MEDICAL PHARMACOLOGY EDUCATION FOR MEDICAL DOCTOR (MD) STUDENTS IN UNIVERSITIES: A COMPREHENSIVE EVIDENCE-BASED CONCEPTUAL FRAMEWORK INTEGRATING PHARMACOLOGY, PHARMACOTHERAPY AND CLINICAL PHARMACOLOGY THROUGH COMPETENCY-BASED, INNOVATIVE, CLINICALLY RELEVANT AND EVIDENCE- INFORMED TEACHING AND LEARNING STRATEGIES

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ABSTRACT

Medical pharmacology education constitutes a foundational component of undergraduate medical education because it establishes the scientific and clinical knowledge required for rational, safe, effective, and patient-centered pharmacotherapy. Nevertheless, conventional approaches to teaching pharmacology at universities frequently remain dominated by content-intensive lectures, fragmented memorization of drug classifications, isolated mechanisms of action, and assessment strategies that inadequately evaluate students' capacity to apply pharmacological knowledge to complex clinical decisions. The increasing complexity of therapeutic regimens, expansion of precision medicine, rapid development of novel pharmacological agents, growing concerns regarding medication-related harm, antimicrobial resistance, polypharmacy, pharmacogenomics, and the increasing availability of biomedical evidence necessitate a fundamental reconsideration of how medical pharmacology is taught and learned by Doctor of Medicine (MD) students. This conceptual paper develops a comprehensive evidence-based educational framework for redefining and enhancing medical pharmacology education through the systematic integration of medical pharmacology, pharmacotherapy, and clinical pharmacology with competency-based, innovative, clinically relevant, and evidence-informed teaching and learning strategies. The proposed framework conceptualizes pharmacology education not as the acquisition of isolated factual knowledge but as a longitudinal process through which students progressively develop integrated scientific reasoning, therapeutic decision-making, prescribing competence, clinical judgment, medication-safety awareness, and professional responsibility. Particular emphasis is placed on connecting pharmacological principles with pathophysiology, clinical diagnosis, therapeutic objectives, pharmacokinetics, pharmacodynamics, adverse drug reactions, drug–drug and drug–disease interactions, contraindications, monitoring requirements, pharmacogenetic considerations, and patient-specific factors. Within this model, Evidence-Based Medicine (EBM) serves as a central educational component, enabling students to formulate clinically relevant questions, identify and critically appraise biomedical literature, evaluate the validity and applicability of evidence, integrate research findings with clinical expertise, and incorporate patient values and preferences into pharmacotherapeutic decision-making. The framework further proposes the integration of active and student-centered educational methodologies, including problem-based learning, case-based learning, team-based learning, simulation-based education, clinical prescribing exercises, structured therapeutic reasoning, flipped classrooms, interactive seminars, digital learning environments, virtual patients, formative assessment, peer learning, and reflective practice. These strategies can transform pharmacology classrooms from predominantly teacher-directed environments into intellectually interactive settings in which students repeatedly apply pharmacological concepts to authentic or simulated clinical problems. Particular attention is directed toward competency-based education, whereby learning outcomes are explicitly linked to observable competencies in medication selection, dose individualization, prescription writing, therapeutic monitoring, adverse-event recognition, risk–benefit assessment, communication, and evidence appraisal. An important dimension of the proposed model is vertical and horizontal curricular integration. Vertical integration connects foundational pharmacological sciences with progressively advanced clinical applications across the MD curriculum, while horizontal integration establishes meaningful relationships between pharmacology and physiology, biochemistry, pathology, microbiology, immunology, internal medicine, surgery, pediatrics, psychiatry, and other clinical disciplines. Such integration may reduce curricular fragmentation and reinforce the relevance of pharmacological knowledge throughout medical training. Furthermore, the framework emphasizes the incorporation of pharmacovigilance, antimicrobial stewardship, rational prescribing, medication reconciliation, deprescribing principles, individualized therapy, and patient-safety competencies as essential

components of contemporary pharmacology education. The conceptual model also recognizes the importance of educational technologies and data-informed pedagogical innovation. Digital resources, electronic prescribing environments, clinical decision-support simulations, adaptive learning platforms, virtual clinical cases, interactive pharmacology databases, and structured EBM exercises can facilitate personalized learning and provide opportunities for repeated practice and immediate feedback. Assessment should consequently evolve beyond conventional recall-based examinations toward multimodal evaluation incorporating clinical vignettes, prescription-writing tasks, objective structured clinical examinations, case analyses, critical appraisal exercises, oral reasoning assessments, portfolios, and longitudinal competency assessment. The proposed framework positions medical pharmacology education as an integrated, clinically oriented, evidence-informed, and competency-driven component of MD education. Its principal objective is to produce future physicians who can move beyond memorizing pharmacological facts toward scientifically justified therapeutic reasoning and responsible medication management. By systematically integrating pharmacology, pharmacotherapy, clinical pharmacology, EBM, innovative pedagogy, patient safety, and competency-based assessment, universities can strengthen the educational foundations of rational prescribing and improve graduates' preparedness for contemporary clinical practice. The framework provides a conceptual basis for curricular reform, faculty development, educational research, and institutional quality improvement, while also highlighting the need for empirical evaluation of its effectiveness across diverse medical education settings.

Keywords: Medical pharmacology education; Clinical pharmacology; Pharmacotherapy education; Evidence-based medicine; Competency-based medical education; Innovative teaching and learning; Medical students.

INTRODUCTION

Medical education is undergoing a profound transformation driven by advances in biomedical science, rapid expansion of therapeutic options, increasing complexity of clinical decision-making, digital transformation of healthcare, changing patterns of disease, medication-safety concerns, and the growing expectation that physicians should be capable of integrating scientific evidence with individualized patient care. Within this transformation, medical pharmacology occupies a particularly important position because medicines represent one of the principal instruments through which physicians prevent, diagnose, control, and treat disease. The quality of pharmacological education therefore has direct implications for prescribing competence, therapeutic effectiveness, patient safety, adverse drug reaction prevention, antimicrobial stewardship, rational medicine use, and the broader quality of healthcare delivery. Contemporary medical students must consequently acquire considerably more than an inventory of drug names, mechanisms, indications, contraindications, and adverse effects. They must learn how to transform pharmacological knowledge into defensible clinical decisions and how to continuously update those decisions as evidence, therapeutic guidelines, patient characteristics, and available treatments evolve.

The educational challenge is intensified by the extraordinary expansion of pharmacological knowledge. Modern pharmacology encompasses molecular targets, receptor biology, signal transduction, pharmacogenomics, pharmacokinetics, pharmacodynamics, immunopharmacology, biologic medicines, targeted therapies, precision therapeutics, drug-delivery technologies, real-world evidence, pharmacovigilance, and increasingly sophisticated clinical decision-support systems. At the same time, the number of medicines available to clinicians continues to increase, while therapeutic recommendations change as new randomized trials, systematic reviews, safety signals, regulatory decisions, and clinical guidelines become available. A curriculum based

primarily on memorization is therefore structurally inadequate for preparing future physicians for a professional environment in which knowledge is dynamic rather than static.

Recent scholarship has explicitly identified the expanding pharmacological knowledge base, changing therapeutic guidelines, curriculum integration, and pedagogical limitations as major challenges for pharmacology education. Fasinu and Wilborn emphasize that future medical pharmacology education requires stronger reliance on active learning, longitudinal integration, problem-based learning, case-based learning, team-based learning, and technology-supported approaches. This perspective reflects a broader transformation in health-professions education from instructor-centered transmission of information toward learner-centered, competency-oriented development.

Traditional lecture-based education remains valuable for establishing conceptual foundations, organizing complex material, and introducing major pharmacological principles. However, lectures alone are insufficient when the intended educational outcome is competent clinical reasoning. A student may correctly recall the mechanism of action of an angiotensin-converting enzyme inhibitor and still be unable to determine whether it is appropriate for a particular patient, select an individualized dose, recognize a clinically significant interaction, identify a contraindication, monitor treatment, or communicate therapeutic risks. The distinction between knowing pharmacology and using pharmacology is therefore fundamental. Contemporary medical pharmacology curricula should deliberately bridge these two domains.

This distinction also explains why pharmacology should not be treated as an isolated preclinical discipline. Pharmacology, pharmacotherapy, and clinical pharmacology constitute interconnected components of therapeutic reasoning. Pharmacology explains how medicines interact with biological systems; pharmacotherapy translates those principles into treatment strategies; and clinical pharmacology applies them to individual patients while accounting for disease characteristics, comorbidities, age, renal and hepatic function, genetics, concomitant medicines, adherence, contraindications, adverse reactions, and patient preferences. When these domains are separated excessively within the curriculum, students may acquire fragmented knowledge without developing an integrated therapeutic mental model.

A contemporary curriculum should consequently promote vertical integration across the medical programme. Fundamental pharmacological concepts introduced during early medical education should reappear and become progressively more clinically sophisticated during subsequent courses and clinical rotations. Receptor pharmacology, pharmacokinetics, dose-response relationships, therapeutic index, adverse drug reactions, drug interactions, and pharmacogenomics should not disappear after completion of a preclinical pharmacology course. Instead, these concepts should be repeatedly activated in cardiovascular medicine, infectious diseases, oncology, psychiatry, neurology, endocrinology, pediatrics, obstetrics and gynecology, anesthesia, emergency medicine, and other clinical environments.

Horizontal integration is equally important. Pharmacology should be connected explicitly with physiology, biochemistry, pathology, microbiology, immunology, genetics, epidemiology, public health, clinical medicine, and diagnostic reasoning. For example, antimicrobial pharmacology becomes substantially more meaningful when students understand microbial pathogenesis, antimicrobial susceptibility, resistance mechanisms, epidemiology, infection control, and clinical diagnostic uncertainty. Similarly, cardiovascular pharmacotherapy becomes more clinically intelligible when students integrate receptor physiology, hemodynamics, pathophysiology, diagnostic criteria, clinical risk stratification, and therapeutic guidelines.

The importance of rational prescribing has been recognized internationally for decades. The World Health Organization's Guide to Good Prescribing was specifically developed for undergraduate medical students and provides a structured approach to rational pharmacotherapy. Its educational philosophy emphasizes learning objectives, patient-oriented cases, treatment selection, critical

evaluation of medical literature, and assessment of practical prescribing competence rather than drug knowledge alone. The WHO approach therefore provides an important conceptual foundation for modern pharmacotherapy education.

Evidence-Based Medicine (EBM) provides another essential dimension of contemporary pharmacology education. Pharmacological decisions are increasingly dependent on the ability to identify and evaluate evidence regarding efficacy, effectiveness, comparative safety, harms, interactions, treatment duration, patient subgroups, and cost-effectiveness. Physicians must be able to recognize that not all evidence has equal methodological strength and that even apparently convincing findings may have limited applicability to a particular patient.

Teaching EBM should therefore begin before students become fully independent clinicians. Medical students should progressively learn to formulate answerable clinical questions, search for relevant evidence, distinguish primary from secondary literature, interpret measures of treatment effect, understand confidence intervals and statistical uncertainty, evaluate risk of bias, assess applicability, and integrate evidence with clinical circumstances and patient values. EBM should not be reduced to a theoretical course in epidemiology or critical appraisal. Its purpose is to establish a habit of evidence-informed clinical reasoning.

The educational literature supports the value of EBM instruction while simultaneously demonstrating important limitations in the evidence base. A systematic review of EBM teaching among medical trainees found improvement in EBM competency after educational interventions but did not establish consistent superiority of one teaching format over another. Similarly, a systematic review of undergraduate medical education reported that seminars, workshops, e-learning, clinically integrated approaches, and multicomponent interventions can improve aspects of EBM knowledge, attitudes, and skills, but the available evidence does not demonstrate that one educational modality is universally superior. These findings support a pluralistic educational strategy rather than dependence upon a single pedagogical technique.

Importantly, the context in which EBM is taught may matter as much as the educational method itself. Evidence from systematic review has suggested that clinically integrated EBM teaching can produce broader improvements than isolated classroom instruction. Consequently, pharmacology education offers an especially appropriate environment for integrating EBM into authentic therapeutic questions. Students can be asked, for example, whether a particular drug class improves clinically meaningful outcomes, whether a new medicine provides an advantage over established therapy, how adverse-event risks compare between alternatives, or whether a treatment recommendation applies to a specific patient population.

Competency-based medical education provides the structural architecture through which these educational objectives can be organized. Competency-based education shifts emphasis from the amount of material delivered toward what learners are demonstrably capable of doing. Within pharmacology, competencies should include accurate pharmacological reasoning, rational selection of medicines, prescription writing, dose individualization, identification of contraindications and interactions, recognition and management of adverse drug reactions, therapeutic monitoring, medication reconciliation, patient counseling, critical appraisal of evidence, and responsible use of clinical decision-support technologies.

A competency framework should also distinguish foundational knowledge from higher-order performance. Students require declarative knowledge of pharmacological principles, but this knowledge should progressively support procedural and conditional knowledge. Procedural knowledge concerns how to perform a task, such as writing an appropriate prescription or calculating a dose. Conditional knowledge concerns when and why a particular therapeutic strategy should be selected. The highest educational objective is therefore not simply remembering pharmacological information but developing a clinically transferable capacity to reason through medication-related problems.

Active learning strategies can support this transition. Problem-based learning requires students to identify learning needs and apply knowledge to clinical problems. Case-based learning places pharmacological principles within realistic patient contexts. Team-based learning promotes preparation, collaborative reasoning, accountability, and application. Flipped learning transfers initial information acquisition outside scheduled classroom time and reserves face-to-face sessions for application, discussion, and problem-solving. Simulation provides opportunities to practice prescribing, monitoring, communication, and management of medication-related emergencies without exposing patients to avoidable risk.

Evidence from pharmacology education increasingly supports multimodal teaching. A large network meta-analysis involving 150 studies and more than 21,000 students reported favorable educational effects associated with combinations of problem-based and case-based learning, team-based learning, and flipped classrooms, although interpretation should account for heterogeneity among interventions and outcomes. A recent review of pharmacology digital simulation likewise found evidence suggesting improvements in knowledge, confidence, and satisfaction, while highlighting the need for stronger integration of polypharmacy and interprofessional learning.

Digital education also changes the role of the pharmacology teacher. Digital platforms can provide interactive drug databases, visualizations of receptor mechanisms, adaptive quizzes, virtual patients, simulated prescribing environments, electronic formularies, clinical decision-support exercises, and immediate formative feedback. These technologies should not simply reproduce lectures electronically. Their educational value depends on whether they promote active cognitive processing, clinical reasoning, retrieval practice, feedback, and transfer.

The emergence of generative artificial intelligence introduces additional opportunities and risks. Recent pharmacology education scholarship identifies AI as both an educational opportunity and a challenge involving personalized feedback, learning support, assessment, and academic integrity. Medical students therefore require AI literacy as part of contemporary evidence-informed pharmacology education. They should learn to use AI-assisted tools critically, verify generated information against authoritative sources, recognize hallucinated or unsupported recommendations, protect patient confidentiality, and retain responsibility for clinical decisions.

Assessment represents another central component of educational reform. If students are assessed predominantly through factual recall, they will rationally devote most of their learning effort to memorization. Assessment should therefore align with intended competencies. Multiple-choice questions remain useful for assessing foundational knowledge, but they should be complemented by clinical vignettes, prescription-writing exercises, structured oral examinations, objective structured clinical examinations, medication-review tasks, critical appraisal exercises, reflective portfolios, and observed clinical performance.

Formative assessment is particularly important. Pharmacological reasoning develops through repeated practice and feedback. Students should have opportunities to make errors in controlled educational environments and receive specific feedback concerning why a therapeutic decision was inappropriate, which pharmacological principle was misunderstood, and how the reasoning process could be improved. Contemporary pharmacology education literature increasingly recognizes formative feedback as an important component of learning, while noting that this area remains underdeveloped relative to other medical education domains.

Another major educational requirement is interprofessional integration. Medication use is not an exclusively physician-controlled process. Pharmacists, nurses, physicians, prescribing specialists, laboratory professionals, and other healthcare professionals contribute to medication safety. Interprofessional education can therefore expose MD students to complementary perspectives concerning prescribing, dispensing, administration, monitoring, adherence, reconciliation, and pharmacovigilance. Recent evidence suggests positive effects of interprofessional interventions

on pharmacological knowledge, prescribing competence, and collaborative attitudes, although implementation can be logistically challenging.

The educational relevance of prescribing competence is particularly important because pharmacological knowledge does not automatically translate into safe prescribing. A recent scoping review identified 80 educational studies addressing pharmacological knowledge or prescribing skills among medical students. The interventions included e-learning, case-based, interprofessional, and experiential learning, with positive findings commonly observed at early Kirkpatrick outcome levels; however, the absence of robust evidence for higher-level clinical outcomes demonstrates the need for stronger educational evaluation.

The proposed conceptual framework therefore rests on several interconnected propositions. First, pharmacology should be longitudinally integrated throughout the MD curriculum rather than confined to an isolated course. Second, pharmacological knowledge should be continuously connected to therapeutic decision-making. Third, EBM should be embedded in pharmacotherapy rather than taught as a disconnected methodological subject. Fourth, competency-based outcomes should determine teaching and assessment. Fifth, active, case-oriented, simulation-supported, digital, and collaborative methods should complement appropriately designed lectures. Sixth, educational technologies should enhance rather than replace expert faculty supervision. Seventh, assessment should evaluate both knowledge and performance. Finally, curriculum reform should be accompanied by rigorous educational evaluation.

This conceptualization responds to a fundamental problem in contemporary medical education: physicians must increasingly manage complex therapeutic decisions in an environment in which information is abundant but attention, time, and cognitive capacity are limited. The purpose of pharmacology education is therefore not merely to increase the quantity of information students remember. Its deeper purpose is to develop physicians capable of identifying therapeutic problems, locating relevant evidence, critically evaluating alternatives, making individualized decisions, monitoring treatment, recognizing harm, communicating with patients, and revising decisions when new evidence emerges.

BACKGROUND

Medical pharmacology historically developed as a predominantly discipline-based scientific subject, emphasizing mechanisms of drug action, drug classification, pharmacokinetic principles, and adverse effects. This structure was appropriate when the principal educational challenge was establishing a foundation in an expanding but comparatively bounded scientific discipline. Contemporary medicine, however, has transformed the knowledge environment. Precision therapeutics, biologics, targeted medicines, immunotherapies, pharmacogenomics, complex combination therapy, digital therapeutics, and rapidly changing clinical guidelines have expanded the scope of therapeutic knowledge considerably.

The evolution of medical curricula toward integrated and competency-based models has consequently changed the position of pharmacology. Recent reviews describe a movement away from isolated, instructor-centered pharmacology toward active, learner-centered and integrated educational approaches. Nevertheless, curricular integration can create a paradox: while integration may improve clinical relevance, excessive fragmentation can cause pharmacology to become invisible within organ-system courses. The solution is not simply to return to a stand-alone pharmacology curriculum but to establish a longitudinal pharmacological thread throughout medical education.

A modern pharmacology curriculum should therefore be constructed around core therapeutic concepts rather than exhaustive lists of medicines. Core concepts should include receptor pharmacology, dose-response relationships, pharmacokinetics, pharmacodynamics, drug interactions, therapeutic windows, adverse drug reactions, medication errors,

pharmacogenomics, principles of antimicrobial therapy, rational prescribing, evidence appraisal, and patient-specific treatment selection.

The WHO prescribing framework provides an important educational precedent because it emphasizes a structured, patient-oriented approach to therapeutic decision-making and encourages students to use treatment guidelines and scientific literature critically. This approach remains highly relevant to competency-based medical education.

Another important background factor is the discrepancy between educational outcomes and clinical outcomes. Much of the literature evaluates immediate knowledge, confidence, satisfaction, or examination performance. The pharmacology educational literature itself recognizes that relatively few studies demonstrate transfer into actual prescribing behavior or patient-level outcomes. Consequently, future curriculum research should move beyond short-term educational endpoints and evaluate whether graduates demonstrate sustained improvement in prescribing quality, medication safety, evidence use, and clinical reasoning.

The current background therefore supports a comprehensive conceptual framework that combines disciplinary knowledge, clinical application, EBM, competency development, educational technology, active learning, simulation, formative assessment, and longitudinal curriculum integration.

Medical pharmacology occupies a distinctive and indispensable position within the education of future physicians because it provides the scientific foundation for understanding medicines and the conceptual basis for rational pharmacotherapeutic decision-making. The discipline connects molecular and cellular mechanisms with physiological responses, pathological processes, therapeutic interventions, adverse effects, and clinical outcomes. For MD students, pharmacology is therefore not merely a body of biomedical knowledge but an essential component of professional competence. Every physician, irrespective of specialty, is expected to make medication-related decisions that are scientifically justified, clinically appropriate, ethically defensible, and responsive to individual patient characteristics. The quality of pharmacology education consequently has implications extending beyond academic achievement to prescribing quality, medication safety, therapeutic effectiveness, prevention of avoidable harm, antimicrobial stewardship, healthcare resource utilization, and patient outcomes.

Historically, pharmacology education developed primarily around the systematic classification of medicines, mechanisms of action, pharmacokinetic and pharmacodynamic principles, therapeutic indications, contraindications, and adverse drug reactions. This disciplinary model contributed substantially to establishing a rigorous scientific foundation for medical education. It enabled students to understand how drugs interact with receptors, enzymes, ion channels, and transporters, signaling pathways, and physiological systems and provided the conceptual vocabulary required for subsequent clinical learning. However, the contemporary therapeutic environment has changed considerably. The volume and complexity of pharmacological knowledge have expanded beyond what can reasonably be mastered through memorization alone. Modern physicians encounter conventional small-molecule medicines alongside monoclonal antibodies, recombinant proteins, cell-based therapies, gene-targeted interventions, immunomodulators, precision medicines, pharmacogenomically guided therapies, advanced drug-delivery systems, and rapidly evolving digital therapeutic technologies.

This expansion creates a fundamental educational challenge. The objective of undergraduate pharmacology can no longer be defined simply as enabling students to remember a large number of drugs and their properties. Instead, students must develop the capacity to identify therapeutic problems, compare pharmacological alternatives, and anticipate benefits and harms, individualize treatment, recognize clinically significant interactions, monitor therapeutic response, interpret emerging evidence, and revise treatment when new information becomes available. The

educational system must therefore move from a predominantly information-centered paradigm toward an application-centered and competency-oriented model.

The distinction between pharmacological knowledge and pharmacological competence is particularly important. Knowledge refers to what the student knows about a drug, whereas competence concerns what the student can appropriately do with that knowledge in a clinical context. A student may be able to accurately state that a particular medicine blocks a receptor, inhibits an enzyme, alters neurotransmitter availability, or modifies an intracellular signaling pathway while remaining unable to determine whether the drug is appropriate for a specific patient. Clinical pharmacological competence requires integration of mechanism, indication, patient characteristics, therapeutic objective, dose, route, duration, contraindications, and interactions, adverse effects, monitoring, and expected clinical outcomes. The educational transition from factual knowledge toward integrated therapeutic reasoning should therefore constitute a central objective of contemporary medical pharmacology curricula.

The changing structure of healthcare further reinforces this requirement. Patients increasingly present with multiple chronic diseases and complex medication regimens. Polypharmacy is common among older adults and individuals with multimorbidity, increasing the potential for drug-drug interactions, drug-disease interactions, prescribing cascades, adherence difficulties, therapeutic duplication, inappropriate dosing, and medication-related harm. The physician must consequently understand not only the pharmacological characteristics of individual medicines but also how medicines behave within complex therapeutic systems. Pharmacology education should prepare students to approach medication regimens as dynamic clinical systems rather than as collections of unrelated prescriptions.

The growth of antimicrobial resistance represents another major reason for strengthening pharmacological education. Rational antimicrobial prescribing requires understanding antimicrobial spectrum, mechanisms of resistance, pharmacokinetic and pharmacodynamic relationships, tissue penetration, dosing strategies, microbiological evidence, and duration of treatment, de-escalation, adverse effects, and ecological consequences. Physicians who lack a sufficiently integrated understanding of antimicrobial pharmacology may contribute unintentionally to inappropriate prescribing and resistance development. Consequently, antimicrobial stewardship should be embedded within pharmacology education rather than introduced only during later clinical training.

Pharmacovigilance represents a similarly important educational domain. Modern physicians must recognize that medicines can produce adverse effects that were not completely predictable from premarketing studies. Students should therefore understand adverse drug reaction classification, causality assessment, signal detection, reporting systems, risk minimization, medication errors, and the importance of post-marketing surveillance. Integrating pharmacovigilance into undergraduate pharmacology can help develop a professional culture in which prescribing is understood as an ongoing process of benefit-risk assessment rather than a one-time decision.

The increasing importance of precision medicine further challenges traditional approaches. Pharmacological response varies among patients because of genetic variation, age, body composition, organ function, comorbidities, environmental exposures, concomitant medicines, adherence, nutritional status, and other determinants. Pharmacogenomics has consequently become increasingly relevant to individualized therapy. MD students need not become pharmacogenetic specialists, but they should understand the principle that genetic and biological heterogeneity can influence drug exposure, therapeutic response, and adverse-event risk. This understanding provides an important conceptual foundation for precision therapeutics.

The educational implications of these developments are substantial. A curriculum that attempts to address therapeutic complexity simply by adding more lectures and more factual content risks increasing cognitive overload without improving clinical competence. The appropriate response is

curricular redesign. The emphasis should shift toward high-value concepts, transferable principles, clinical application, retrieval and reinforcement, deliberate practice, evidence appraisal, and longitudinal integration. Students should learn fewer isolated facts and develop stronger conceptual structures through which new pharmacological information can subsequently be incorporated.

Curricular integration is therefore a central principle of modern pharmacology education. Vertical integration refers to the deliberate progression of pharmacological knowledge from early foundational education into later clinical learning. Concepts introduced during preclinical pharmacology should recur during clinical medicine, allowing students to reinterpret foundational mechanisms within increasingly complex clinical situations. For example, principles of receptor selectivity introduced during basic pharmacology can later be applied to cardiovascular, endocrine, neurological, psychiatric, and respiratory therapeutics. Similarly, pharmacokinetic principles should progressively evolve into clinical competence involving dose adjustment, therapeutic drug monitoring, renal impairment, hepatic dysfunction, drug interactions, and individualized treatment.

Horizontal integration connects pharmacology with other disciplines taught at comparable stages of the curriculum. Pharmacological decision-making is inseparable from physiology, pathology, biochemistry, microbiology, immunology, genetics, epidemiology, and clinical medicine. A drug's mechanism becomes more meaningful when students understand the physiological or pathological pathway it modifies. An antimicrobial regimen becomes more understandable when students integrate microbiology and infectious-disease principles. An immunomodulatory medicine becomes more intelligible when students understand immune mechanisms and disease pathogenesis. Horizontal integration therefore reduces artificial disciplinary boundaries and promotes the development of coherent clinical mental models.

The concept of the spiral curriculum provides a useful theoretical basis for such integration. Core concepts should be introduced at an appropriate level, revisited repeatedly, and progressively expanded in complexity. The student should encounter pharmacology not as a single educational event but as a continuously developing body of knowledge. Repetition in this context does not mean unnecessary duplication. Rather, the same core concepts are revisited in increasingly sophisticated contexts, enabling students to develop deeper understanding and transfer knowledge to new clinical situations.

The increasing complexity of pharmacotherapy also creates a strong rationale for integrating clinical pharmacology with medical pharmacology. Medical pharmacology traditionally emphasizes mechanisms and general drug effects, whereas clinical pharmacology focuses more directly on the use of medicines in humans, including dose optimization, therapeutic drug monitoring, drug interactions, pharmacogenetics, adverse reactions, clinical trials, and individualized therapy. Pharmacotherapy adds another dimension by emphasizing the selection and implementation of treatment for specific clinical conditions. Separating these domains excessively can create fragmented learning. Their integration provides a more authentic representation of how medicines are actually used in clinical practice.

Rational prescribing should therefore become a core outcome of pharmacology education. The physician should be capable of defining a therapeutic objective, identifying suitable treatment alternatives, selecting the most appropriate medicine for an individual patient, determining an appropriate dose and regimen, providing relevant instructions, evaluating effectiveness, monitoring safety, and modifying treatment when required. This process is fundamentally different from memorizing drug classifications. It requires clinical reasoning, pharmacological knowledge, evidence appraisal, communication skills, and professional judgment.

The World Health Organization's rational prescribing framework provides an important foundation for this educational orientation. Its approach emphasizes structured therapeutic decision-making

and encourages medical students to select medicines according to individual patient characteristics and therapeutic objectives rather than simply reproducing lists of commonly used drugs. Such an approach remains highly relevant because it establishes a direct connection between pharmacological science and clinical responsibility.

Evidence-Based Medicine represents a further essential component of this transformation. Contemporary pharmacological decisions are made within an environment characterized by a continuous flow of new evidence. Randomized controlled trials, systematic reviews, meta-analyses, clinical guidelines, pharmacovigilance reports, observational studies, real-world evidence, and regulatory communications can all influence therapeutic decisions. Physicians therefore require the ability to determine which evidence is relevant, how reliable it is, and whether its conclusions are applicable to a particular patient.

The integration of Evidence-Based Medicine into pharmacology education should begin during undergraduate medical training. Students should learn to formulate answerable therapeutic questions using structured frameworks, identify appropriate information sources, search biomedical databases, distinguish different forms of evidence, assess study design, recognize sources of bias, interpret effect measures, understand confidence intervals, evaluate statistical and clinical significance, and determine applicability to individual patients. These skills should be repeatedly reinforced through pharmacological cases rather than being confined to an isolated research-methodology course.

An important distinction should be maintained between evidence-based medicine and evidence-only medicine. Clinical decision-making cannot be reduced to the mechanical application of published findings. Evidence must be integrated with clinical expertise, patient characteristics, patient values and preferences, resource considerations, and the practical context of care. Pharmacology education should therefore teach students to use evidence as an instrument of clinical reasoning rather than as a substitute for professional judgment.

The available literature supports EBM education but also demonstrates methodological heterogeneity. Systematic reviews have reported improvements in knowledge and critical appraisal skills following educational interventions, while evidence for sustained changes in clinical behavior is less consistent. This observation is particularly important for pharmacology education because an intervention that improves examination performance does not necessarily produce better prescribing. Educational research should consequently increasingly evaluate transfer, retention, performance, and clinical relevance.

Competency-based medical education provides an appropriate educational architecture for addressing these challenges. Competency-based education focuses on what learners are capable of demonstrating rather than simply what content has been delivered. In pharmacology, this means specifying competencies that can be observed and assessed. These competencies may include explaining pharmacological mechanisms, selecting appropriate medicines, individualizing doses, recognizing contraindications, identifying interactions, writing safe prescriptions, monitoring treatment, recognizing adverse drug reactions, applying pharmacovigilance principles, evaluating evidence, communicating medication information, and collaborating with other healthcare professionals.

Competency development should be progressive. Early medical students may demonstrate competence through controlled case exercises and structured questions. More advanced students should demonstrate the ability to manage increasingly complex cases involving multimorbidity, polypharmacy, organ dysfunction, adverse reactions, therapeutic failure, adherence challenges, and competing therapeutic priorities. During clinical rotations, students should apply pharmacological competencies within authentic patient-care environments under appropriate supervision.

Problem-based learning provides one mechanism for developing this type of competence. Rather than beginning with an exhaustive lecture on a drug class, students may begin with a clinical problem that requires pharmacological investigation. They must identify what they know, determine what they need to learn, formulate therapeutic questions, consult evidence, and justify a treatment strategy. This approach transforms pharmacology from a passive knowledge-acquisition activity into an active reasoning process.

Case-based learning offers another powerful strategy. Clinical cases can be designed to require students to integrate pharmacological principles with diagnosis, pathophysiology, patient-specific factors, evidence, and therapeutic monitoring. The complexity of cases can be increased progressively. Introductory cases may involve uncomplicated single-drug therapy, whereas advanced cases may involve multiple medicines, renal impairment, hepatic dysfunction, drug interactions, genetic variation, pregnancy, older age, treatment failure, or serious adverse reactions.

Team-based learning can further strengthen pharmacological reasoning by requiring students to prepare individually and then solve application problems collaboratively. Pharmacotherapy frequently involves uncertainty and competing alternatives. Group discussion makes the reasoning process visible and allows students to compare therapeutic judgments. It can also develop communication and interprofessional skills required for safe medication management.

Flipped learning provides another mechanism for reallocating instructional time. Foundational information can be delivered through concise lectures, recorded materials, readings, or interactive digital resources before classroom sessions. Classroom time can then be dedicated to clinical cases, prescribing exercises, therapeutic calculations, evidence appraisal, discussion, and feedback. The educational value of the flipped classroom therefore depends not simply on moving lectures online but on using face-to-face time for higher-order learning.

Simulation is particularly valuable for medication-related education because it enables students to practice clinical decisions without exposing patients to unnecessary risk. Virtual patients, electronic prescribing platforms, simulated medication charts, clinical decision-support environments, and adverse-drug-reaction scenarios can provide repeated opportunities to practice. Simulation can also introduce realistic uncertainty, time pressure, incomplete information, and changing clinical conditions.

Digital technologies have transformed the educational environment further. Pharmacology students can access electronic drug databases, guideline repositories, interactive mechanism-of-action models, clinical calculators, virtual laboratories, digital flashcards, adaptive assessment systems, and online evidence resources. Properly designed digital learning can support self-directed learning, immediate feedback, spaced retrieval, and personalized progression. However, technology should serve educational objectives rather than become an objective in itself.

The emergence of artificial intelligence adds another layer of complexity. AI systems can generate explanations, create practice questions, simulate clinical interactions, assist information retrieval, and potentially personalize learning. However, pharmacological misinformation generated by AI could have serious educational consequences if students accept inaccurate recommendations without verification. Consequently, AI literacy should become part of contemporary medical pharmacology education. Students should learn to interrogate AI outputs, verify claims against authoritative sources, recognize uncertainty, distinguish generated text from validated evidence, and maintain professional responsibility for therapeutic decisions.

The increasing availability of digital resources also raises concerns regarding information overload. Access to large quantities of information does not automatically produce knowledge or competence. Students need information-literacy skills enabling them to determine which sources are authoritative, current, relevant, and methodologically credible. Pharmacology education

should therefore teach not only drug knowledge but also information navigation and source evaluation.

Assessment is one of the strongest determinants of learning behavior. If pharmacology examinations emphasize factual recall, students will naturally prioritize memorization. If the intended outcome is clinical competence, assessment must require clinical application. Traditional multiple-choice examinations remain useful for testing foundational knowledge, but they should be complemented by clinical vignettes, prescription-writing exercises, dose-calculation tasks, medication-review cases, OSCE stations, critical appraisal exercises, structured oral examinations, and portfolios.

Assessment should also be aligned with competency progression. Early assessment may focus on knowledge and conceptual understanding. Intermediate assessment should evaluate application and reasoning. Advanced assessment should evaluate integrated clinical performance. Such alignment creates constructive coherence between learning objectives, teaching strategies, and evaluation.

Formative assessment is particularly important in pharmacology because errors in therapeutic reasoning can be identified and corrected before students enter independent clinical practice. Feedback should be timely, specific, actionable, and connected to the reasoning process. Rather than simply indicating that an answer is incorrect, educators should explain which pharmacological principle was misunderstood, what patient factor was overlooked, how the evidence should have been interpreted, and what reasoning pathway would have produced a safer decision.

Medication safety should constitute an explicit educational outcome. Medication errors may arise from inappropriate prescribing, incorrect dose selection, contraindications, interactions, communication failures, inadequate monitoring, or failure to recognize patient-specific risks. Students should therefore learn medication reconciliation, allergy assessment, interaction checking, high-risk medicines and transitions of care, prescription clarity, monitoring plans, and patient counseling.

Patient-centered care is equally important. Pharmacological decisions are not made for abstract disease categories; they are made for individual patients. Patients may have different preferences, treatment goals, risk tolerances, socioeconomic circumstances, adherence barriers, health literacy levels, and expectations. Students should therefore learn how to communicate the benefits, risks, alternatives, uncertainties, and practical requirements of treatment in a manner that supports shared decision-making.

Interprofessional education provides an additional dimension. Safe medication management involves multiple healthcare professionals, including physicians, pharmacists, nurses, and other specialists. Medical students should understand the complementary responsibilities of these professionals. Collaborative medication-review exercises can demonstrate how communication failures or incomplete information can contribute to medication-related harm and how coordinated practice can mitigate such risks.

The pharmacist's role is particularly relevant to modern pharmacology education. Pharmacists possess specialized expertise in pharmacotherapy, medication safety, interactions, adherence, and medication-use systems. Collaboration between pharmacology educators, clinical pharmacologists, pharmacists, and practicing physicians can enrich MD curricula and provide students with multiple perspectives on medication management. Interprofessional educational models may also help reduce the artificial separation between prescribing, dispensing, administration, monitoring, and follow-up.

Faculty development is therefore an essential prerequisite for successful curriculum transformation. Educators who have themselves been trained primarily through traditional lecture-based approaches may require structured development in active learning, case construction, simulation facilitation, EBM teaching, digital pedagogy, competency assessment,

and feedback. Faculty members also need opportunities to evaluate and disseminate their educational innovations through scholarship.

Institutional factors are equally important. Curriculum reform requires appropriate allocation of teaching time, technological infrastructure and access to reliable pharmacological information resources, simulation facilities, assessment capacity, and faculty support. Educational innovation cannot be sustained if it depends entirely on individual enthusiasm without institutional recognition and resources.

The internationalization of medical education adds another dimension. MD programmes increasingly educate students who will practice across different healthcare systems and regulatory environments. Pharmacology education should therefore emphasize transferable principles of therapeutic reasoning rather than dependence on a single national formulary. At the same time, students should understand that medicine availability, prescribing regulations, treatment guidelines, antimicrobial resistance patterns, pharmacovigilance systems, and healthcare resources vary across countries.

Global health considerations should also be incorporated. The rational use of medicines has implications for health equity, access, affordability, antimicrobial resistance, essential medicines, and resource allocation. Students should understand that pharmacological decision-making occurs within broader health systems and that clinically appropriate treatment must also be considered in relation to availability, sustainability, and equitable access.

Another important background consideration is the distinction between efficacy and effectiveness. Students traditionally learn about efficacy through controlled clinical trials, but real-world treatment outcomes may differ because of adherence, comorbidities, polypharmacy, health-system constraints, and differences between trial populations and clinical populations. EBM education should therefore introduce students to both internal validity and external validity and encourage critical evaluation of whether study findings apply to individual patients.

Similarly, students should understand the distinction between relative and absolute treatment effects. Therapeutic decisions are frequently influenced by relative risk reductions that can appear impressive without conveying the absolute magnitude of benefit. Teaching pharmacology through evidence-based cases provides an opportunity to introduce measures such as absolute risk reduction, relative risk, number needed to treat, number needed to harm, confidence intervals, and treatment heterogeneity.

Clinical guidelines should also be incorporated carefully. Guidelines provide structured recommendations, but they are not substitutes for individualized judgment. Students should learn to identify the strength and certainty of guideline recommendations, understand conflicts of interest and evidence limitations, and recognize circumstances in which individual patient factors justify deviation from standard recommendations.

Real-world evidence and post-marketing data have become increasingly important in this context. Randomized trials remain fundamental for evaluating efficacy, but observational data can provide important information regarding long-term safety, rare adverse reactions, treatment patterns, adherence, and effectiveness in broader populations. Contemporary pharmacology education should expose students to the complementary roles of randomized and observational evidence.

The concept of therapeutic uncertainty should also become more explicit. Medicine frequently involves incomplete evidence, competing treatment options, and uncertain risk. Students should not be taught that every pharmacological question has a single universally correct answer. Instead, they should learn how to make defensible decisions under uncertainty and communicate that uncertainty appropriately.

Ethical considerations are inseparable from pharmacotherapy. Prescribing decisions involve benefit-risk assessment, informed consent, autonomy, equity, resource utilization, conflicts of interest, pharmaceutical marketing, and responsible professional behavior. Students should

understand that pharmacological knowledge creates professional obligations. A physician's decision to prescribe a medicine can expose a patient to substantial benefit or harm and should therefore be grounded in scientific evidence and ethical reasoning.

Commercial influences also warrant educational attention. Pharmaceutical marketing can affect prescribing behavior and perceptions of therapeutic value. Students should learn to distinguish promotional information from independent evidence and recognize potential conflicts of interest in research, guideline development, and educational materials. Critical appraisal should therefore encompass not only study methodology but also funding sources, author conflicts, selective reporting, and publication bias.

The educational environment should additionally support lifelong learning. Pharmacological knowledge becomes outdated rapidly, particularly in fields characterized by accelerated therapeutic innovation. The most important long-term educational outcome is therefore not memorization of every currently available medicine but the development of reliable strategies for continuing professional learning. Graduates should know how to identify knowledge gaps, search authoritative sources, evaluate new evidence, and update therapeutic decisions throughout their careers.

The transition from student to physician consequently requires a shift from externally supplied information toward self-directed professional learning. Pharmacology education should explicitly model this process. Faculty members can demonstrate how they approach unfamiliar therapeutic questions, identify authoritative resources, evaluate new evidence, and incorporate emerging findings into practice. Such modeling can help students understand that uncertainty and continuing learning are normal features of clinical pharmacology.

Another major consideration is educational equity. Digital and innovative educational strategies should not inadvertently create disparities among students. Differences in access to technology, learning resources, language proficiency, prior knowledge, and financial circumstances can influence educational outcomes. Universities should therefore ensure that innovation is accompanied by appropriate institutional support and equitable access to learning resources.

The COVID-19 pandemic accelerated the adoption of online and hybrid medical education and demonstrated both the potential and limitations of digital learning. Pharmacology education can benefit from this experience by retaining effective digital resources while avoiding the assumption that online delivery alone constitutes educational innovation. Human interaction, clinical exposure, mentorship, discussion, feedback, and authentic practice remain essential components of medical education.

Educational quality should consequently be evaluated systematically. Universities should establish measurable indicators for pharmacology education, including student knowledge, prescribing performance, critical appraisal skills, clinical reasoning, medication-safety competencies, learner engagement, retention, and graduate performance. Educational interventions should be subjected to rigorous evaluation using validated assessment instruments whenever possible.

The Kirkpatrick framework can provide a useful starting point for evaluating educational interventions, but evaluation should extend beyond learner satisfaction and immediate knowledge gains. The most meaningful question is whether education changes behavior and improves performance. In pharmacology, this could include whether graduates prescribe more appropriately, identify contraindications more reliably, recognize adverse drug reactions more effectively, use evidence more consistently, and communicate medication decisions more safely.

The literature nevertheless demonstrates an important research gap. Many educational studies assess short-term outcomes, whereas relatively few evaluate long-term retention, transfer to clinical settings, or patient-level outcomes. There is therefore a need for multicenter educational research examining longitudinal curricular interventions and their effects on prescribing

competence. Standardized outcome measures would facilitate comparison between universities and educational systems.

The proposed conceptual framework responds to these limitations by organizing medical pharmacology education around a coherent progression from foundational scientific knowledge to clinical application, evidence appraisal, professional competence, and lifelong learning. It does not advocate the abandonment of lectures or traditional examinations. Rather, it proposes their repositioning within a broader educational ecosystem. Lectures remain valuable for introducing complex conceptual material, while active learning, clinical cases, simulation, EBM exercises, prescribing practice, and assessment provide opportunities for application and integration.

The framework can therefore be understood as a multidimensional educational architecture. At its foundation is scientific pharmacology. The next level is therapeutic reasoning, through which students connect mechanisms with clinical objectives. The third level is Evidence-Based Medicine, through which students evaluate and apply external evidence. The fourth level is clinical performance, involving prescribing, monitoring, communication, and medication management. The fifth level is professional responsibility, including patient safety, pharmacovigilance, ethics, stewardship, and interprofessional collaboration. The final level is lifelong learning, enabling physicians to continuously update their therapeutic knowledge.

This architecture recognizes that competent prescribing is an emergent capability resulting from the interaction of multiple forms of knowledge. Scientific knowledge without clinical reasoning may remain academically sophisticated but therapeutically ineffective. Clinical experience without evidence appraisal may produce habitual rather than evidence-informed prescribing. EBM without pharmacological understanding may produce superficial application of recommendations. Competency therefore requires integration.

The ultimate purpose of reforming pharmacology education is not simply to produce students who perform better on pharmacology examinations. It is to produce physicians who can make better therapeutic decisions. This distinction should guide curriculum design, teaching methods, assessment, faculty development, and educational research.

A comprehensive university-based medical pharmacology curriculum should consequently cultivate a physician who can understand the biological basis of drug action, identify clinically relevant therapeutic problems, formulate answerable questions, retrieve and appraise evidence, select individualized therapy, prescribe accurately, anticipate and monitor adverse effects, identify interactions, communicate with patients, collaborate with healthcare professionals, evaluate outcomes, and modify treatment when evidence or patient circumstances change.

Such a physician is not merely pharmacologically knowledgeable. The physician is pharmacologically competent, clinically reasoning, evidence-informed, patient-centered, safety-conscious, and capable of lifelong therapeutic learning. This represents the central educational rationale for redefining medical pharmacology, pharmacotherapy, and clinical pharmacology education within contemporary MD programmes.

Accordingly, the background to the present conceptual framework is characterized by a convergence of scientific expansion, therapeutic complexity, patient-safety demands, curricular transformation, evidence-based practice, technological innovation, competency-based education, and changing expectations of physicians. These developments collectively demonstrate the necessity of moving beyond traditional content-heavy pharmacology instruction toward an integrated educational model capable of preparing MD students for the realities of modern pharmacotherapy. The proposed framework seeks to provide such a model by connecting scientific pharmacology with clinical practice, Evidence-Based Medicine, innovative pedagogy, competency development, medication safety, interprofessional collaboration, and continuous professional learning.

GOAL

The primary goal of this conceptual study is to develop a comprehensive, evidence-informed educational framework for redefining and enhancing medical pharmacology education for MD students at universities through the longitudinal integration of medical pharmacology, pharmacotherapy, and clinical pharmacology with competency-based education, Evidence-Based Medicine, innovative pedagogy, clinical reasoning, digital learning, simulation, interprofessional education, and authentic assessment.

The specific objectives are to: (1) identify major limitations of traditional pharmacology education; (2) establish core pharmacological and therapeutic competencies for MD students; (3) integrate EBM into pharmacology and pharmacotherapy learning; (4) identify educational strategies capable of strengthening knowledge application and therapeutic reasoning; (5) develop an integrated model linking foundational science to clinical prescribing; (6) propose assessment approaches aligned with competency development; (7) incorporate digital and simulation technologies responsibly; and (8) formulate recommendations for university-level curricular reform and faculty development.

METHODOLOGY

This article employs a conceptual, evidence-informed narrative synthesis methodology. Relevant scientific and educational literature was identified through searches of PubMed/MEDLINE and major biomedical and medical-education literature sources, supplemented by authoritative international educational guidance and reference tracking. Search concepts included combinations of medical pharmacology education, pharmacotherapy education, clinical pharmacology, prescribing competence, medical students, competency-based medical education, evidence-based medicine, active learning, problem-based learning, case-based learning, team-based learning, simulation, digital learning, pharmacology assessment, and clinical reasoning.

Priority was given to systematic reviews, scoping reviews, meta-analyses, educational research, authoritative guidance, and contemporary conceptual literature. Particular attention was given to literature addressing undergraduate medical students and the transfer of pharmacological knowledge into prescribing or clinical reasoning. The evidence was critically synthesized thematically rather than statistically pooled because the educational literature demonstrates substantial heterogeneity in intervention design, curriculum structure, learner populations, assessment instruments, educational settings, and outcome measures.

The conceptual synthesis was organized around six domains: foundational pharmacological knowledge; pharmacotherapeutic and prescribing competence; EBM competence; innovative teaching and learning; clinical integration and interprofessional learning; and assessment and quality improvement. Findings from these domains were subsequently synthesized into a longitudinal educational framework.

Because this article is conceptual rather than a primary intervention study, no new human participants, patient data, biological specimens, or identifiable clinical information were used. The “results” represent synthesized findings from published educational evidence and the resulting conceptual model.

RESULTS AND DISCUSSION

The present conceptual investigation demonstrates that contemporary medical pharmacology education requires a fundamental transition from a predominantly content-oriented instructional paradigm toward an integrated educational architecture centered on pharmacological competence, therapeutic reasoning, evidence-informed decision-making, prescribing safety, clinical applicability, and lifelong professional learning. The synthesis of available educational literature indicates that the central problem confronting medical pharmacology education is not

an absence of educational resources or pharmacological knowledge, but a persistent discrepancy between the acquisition of theoretical information and the ability of MD students to apply that information appropriately in clinically complex situations. The findings consequently support the development of an integrated model in which medical pharmacology, pharmacotherapy, clinical pharmacology, Evidence-Based Medicine, clinical reasoning, innovative pedagogy, simulation, interprofessional education, digital learning, and competency-based assessment are progressively interconnected throughout the medical curriculum.

A major finding is that pharmacological knowledge remains an indispensable foundation of medical education but is insufficient as an isolated educational outcome. Pharmacology provides the scientific explanation for how medicines interact with biological systems, but prescribing requires considerably more than mechanistic understanding. A competent physician must determine whether treatment is indicated, identify an appropriate therapeutic objective, select among alternatives, consider patient-specific characteristics, calculate and individualize dosage, anticipate interactions and contraindications, communicate treatment instructions, establish monitoring parameters, evaluate therapeutic effectiveness, recognize adverse reactions, and modify treatment when circumstances change. The available literature confirms that prescribing represents a complex combination of knowledge, skills, and attitudes rather than a simple recall task. Evidence concerning graduating medical students has also identified important deficiencies in prescribing competence, particularly in general prescribing, antimicrobial prescribing, and pharmacovigilance, supporting the need for stronger undergraduate clinical pharmacology and therapeutics education.

The findings therefore support a distinction between pharmacological knowledge, pharmacological application, and pharmacological competence. Pharmacological knowledge encompasses factual and conceptual understanding of medicines and their biological effects. Pharmacological application involves using this knowledge to analyze clinical situations. Pharmacological competence represents the ability to perform appropriate therapeutic decisions consistently, safely, and professionally. A modern curriculum should progressively move learners through all three levels. Educational programmes that concentrate almost exclusively on the first level may produce students capable of passing written examinations while remaining inadequately prepared for real-world prescribing.

The evidence further indicates that the traditional separation between pharmacology and pharmacotherapy is educationally problematic. Medical pharmacology provides the scientific basis for understanding treatment, whereas pharmacotherapy requires the translation of this knowledge into decisions concerning individual patients. Clinical pharmacology occupies the interface between these domains by addressing the use of medicines in human beings, including pharmacokinetic variability, pharmacodynamic response, therapeutic drug monitoring, interactions, adverse drug reactions, pharmacogenomics, clinical trials, and individualized therapy. The conceptual synthesis therefore identifies integration of these three domains as a central educational requirement.

A second major finding concerns the organization of the curriculum. The evidence supports longitudinal integration rather than concentration of pharmacology within a single early preclinical block. The most educationally coherent structure is a spiral model in which fundamental pharmacological principles are introduced early, revisited during organ-system education, and subsequently applied in clinical clerkships. This approach allows students to encounter the same concepts at progressively greater levels of complexity. For example, basic pharmacokinetics can initially be taught through simple dose-concentration relationships and subsequently revisited through renal impairment, hepatic dysfunction, therapeutic drug monitoring, drug interactions, and individualized dosing. Such repetition reinforces knowledge while progressively converting theoretical understanding into clinical competence.

The findings also indicate that horizontal curricular integration is essential. Pharmacology should be connected with physiology, biochemistry, pathology, microbiology, immunology, genetics, epidemiology, and clinical medicine. A pharmacological mechanism becomes substantially more meaningful when students understand the biological process being modified. Similarly, antimicrobial therapy is more effectively understood when pharmacology is linked to microbiological diagnosis, resistance mechanisms, susceptibility testing, infection control, and clinical severity. Cardiovascular pharmacotherapy becomes more comprehensible when students integrate receptor pharmacology with cardiovascular physiology, pathophysiology, risk stratification, and clinical outcomes.

The synthesis demonstrates that clinical relevance is one of the most important determinants of meaningful pharmacology learning. Students frequently perceive pharmacology as information-intensive because many conventional teaching strategies present medicines as lists of drug classes, mechanisms, indications, adverse effects, and contraindications. When these facts are presented without clinical context, students may experience cognitive overload and have difficulty determining which information is most important. By contrast, clinically situated learning gives pharmacological information a functional purpose. The question changes from “What are the adverse effects of this drug?” to “Which adverse effects are clinically important in this patient, how would you recognize them, and what would you do if they occurred?” This transformation promotes deeper learning.

The evidence on educational interventions strongly reinforces this conclusion. A comprehensive scoping review of 80 studies involving medical students found a broad range of approaches, including e-learning, case-based learning, interprofessional learning, experiential education, and other innovative methods. All included studies reported at least one positive outcome at Kirkpatrick level 1 or 2, although none demonstrated outcomes at levels 3 or 4. This finding is simultaneously encouraging and cautionary: educational interventions appear capable of improving immediate learning and learner responses, but evidence that these gains translate into sustained changes in clinical behavior or patient outcomes remains insufficient.

The major finding is that case-based learning represents a particularly appropriate pedagogical bridge between pharmacological science and therapeutic decision-making. Pharmacological cases allow students to apply mechanisms and principles in realistic contexts. The educational value of a case depends on its construction. A superficial case may simply ask students to identify a drug. A sophisticated case requires them to determine the therapeutic objective, evaluate the patient's clinical characteristics, compare alternatives, justify the selected medicine, calculate the dose, anticipate adverse effects, identify monitoring requirements, and explain the decision using current evidence.

Case complexity should increase progressively throughout the MD programme. Early cases should focus on relatively straightforward therapeutic problems. Intermediate cases can introduce comorbidity, altered pharmacokinetics, drug interactions, and adherence problems. Advanced cases should include multimorbidity, polypharmacy, organ dysfunction, treatment failure, adverse drug reactions, antimicrobial resistance, pregnancy, geriatric considerations, genetic variation, and competing therapeutic priorities. This progressive design allows the learner to develop increasingly sophisticated therapeutic schemas.

The finding is that prescribing education should be explicitly integrated into pharmacology rather than assumed to emerge automatically from pharmacological knowledge. The systematic review of educational interventions for medical students found that additional prescribing education was associated with improved prescribing skills in 11 of 12 included studies. Interventions included case-based teaching, patient-based learning, and tutorials, didactic teaching, and mixed approaches. These findings suggest that prescribing competence is teachable and that structured educational exposure can produce measurable improvement.

However, the evidence also reveals considerable heterogeneity. There is no universally accepted optimal educational modality, assessment instrument, timing, or duration for prescribing education. This heterogeneity should not be interpreted as evidence that prescribing education lacks value. Rather, it demonstrates that universities require curriculum-level coherence. A single prescribing workshop is unlikely to produce durable competence. Prescribing should be introduced early, practiced repeatedly, assessed progressively, and reinforced during clinical rotations.

The finding concerns the World Health Organization rational-prescribing approach as an important conceptual foundation. The six-step prescribing process provides a practical structure through which students can move from defining the patient's problem to specifying therapeutic objectives, verifying treatment suitability, initiating treatment, providing information, monitoring effects, and reassessing the therapeutic decision. The educational value of such a framework is that it transforms pharmacology into an organized clinical process. Rather than memorizing isolated drug characteristics, students learn how pharmacological information contributes to a sequence of therapeutic decisions.

The finding is the importance of Evidence-Based Medicine as an integral component of pharmacological reasoning. Modern physicians cannot safely depend exclusively on memorized pharmacological knowledge because therapeutic evidence changes continuously. New randomized trials, systematic reviews, pharmacovigilance signals, regulatory communications, and clinical guidelines may alter the perceived balance of benefit and risk of established therapies. Medical students must therefore learn how to identify, evaluate, and apply current evidence.

The evidence concerning EBM education supports this approach but also identifies significant limitations. A systematic review of undergraduate medical education found that several EBM approaches improved knowledge, attitudes, or skills, but the available evidence did not demonstrate superiority of one educational method. Furthermore, long-term transfer into clinical practice was insufficiently studied. This finding supports a blended model rather than methodological exclusivity.

The findings suggest that EBM should be clinically embedded rather than compartmentalized. A student learning cardiovascular pharmacology, for example, should not only know the mechanism of a drug class but should also be able to formulate a therapeutic question concerning comparative effectiveness or safety, locate an appropriate systematic review or clinical guideline, assess the credibility of the evidence, interpret treatment effects, and determine whether the evidence applies to the patient under consideration. Such integration transforms EBM from an abstract methodological discipline into a practical clinical skill.

Evidence from broader medical education also supports clinical integration. A systematic review comparing standalone and clinically integrated EBM education found that standalone approaches improved knowledge but did not consistently improve skills, attitudes, or behavior, whereas clinically integrated approaches demonstrated broader improvements. Although these findings derive principally from postgraduate education, their educational principle is directly relevant to undergraduate pharmacology: evidence appraisal is most likely to become meaningful when learners use it to solve authentic clinical problems.

The finding concerns active learning. Pharmacology requires students to integrate multiple concepts simultaneously, making it particularly suitable for learning strategies that require active cognitive engagement. Problem-based learning, case-based learning, team-based learning, peer instruction, concept mapping, retrieval practice, and structured discussion can all encourage students to retrieve and apply knowledge rather than passively receive information.

The evidence indicates that active learning should not necessarily replace all conventional instruction. Short, carefully structured lectures remain useful for introducing difficult concepts, correcting misconceptions, and organizing large bodies of knowledge. The more appropriate

model is therefore a blended pedagogical system. Direct instruction should establish conceptual foundations, whereas active learning should provide opportunities for application, integration, and reasoning.

The finding is that problem-based learning can improve the clinical meaningfulness of pharmacology when cases are appropriately designed. In problem-based learning, students encounter a clinical problem before receiving a complete explanation. They identify their knowledge gaps, formulate learning objectives, seek information, and subsequently apply what they have learned. This process mirrors clinical practice, where physicians frequently encounter unfamiliar therapeutic questions and must independently acquire relevant knowledge.

Nevertheless, problem-based learning should not be regarded as inherently superior to all other methods. Its effectiveness depends on facilitation quality, case design, learner preparation, group dynamics, curricular timing, and assessment alignment. The evidence therefore supports selective and purposeful use rather than universal replacement of lectures.

The finding concerns team-based learning and collaborative reasoning. Pharmacotherapy frequently involves competing therapeutic alternatives. Collaborative discussion enables students to explain why one treatment might be preferred over another and to identify assumptions underlying different decisions. This can expose misconceptions that may remain invisible during individual study.

Team-based learning also develops communication and accountability. Students must prepare before class, demonstrate individual understanding, discuss application problems, and reach group decisions. These processes resemble clinical environments in which therapeutic decisions are frequently discussed within multidisciplinary teams.

The finding concerns interprofessional education. Recent evidence specifically addressing pharmacology and prescribing found positive effects across pharmacological knowledge, prescribing skills, and interprofessional attitudes. A 2025 scoping review identified 42 studies involving medical students and trainees; interventions included case-based learning, work-integrated learning, didactic education, simulation, and role-play. The studies reported positive findings across several Kirkpatrick levels, although logistical barriers to large-scale implementation remained important.

These findings have major implications for university curricula. Medication safety is inherently interprofessional. Physicians prescribe, pharmacists evaluate and dispense medicines, nurses administer many treatments and monitor patients, and multiple professionals contribute to medication reconciliation, education, and pharmacovigilance. Educational experiences should therefore expose students to the interconnectedness of these responsibilities.

The finding is that experiential learning should receive greater attention. Classroom-based instruction cannot fully reproduce the complexity of medication use in clinical environments. Students should have opportunities to observe and participate in medication reconciliation, prescribing review, therapeutic monitoring, patient counseling, adverse-event reporting, and multidisciplinary treatment planning under appropriate supervision.

Experiential learning should be structured rather than passive. Students should receive defined objectives, preparation activities, observation criteria, opportunities for participation, and structured reflection. Reflection is particularly valuable because it enables learners to identify discrepancies between theoretical pharmacology and actual clinical decision-making.

The finding concerns simulation-based education. Simulation can reproduce medication-related situations that are difficult to encounter reliably during routine clinical rotations. Examples include high-risk prescribing, severe adverse drug reactions, medication errors, anticoagulation problems, antimicrobial stewardship decisions, polypharmacy, drug interactions, and emergency pharmacotherapy.

Simulation is especially valuable for patient-safety education because errors can be analyzed without causing patient harm. Students can be required to identify an incorrect prescription, recognize a contraindication, correct a dose, respond to an adverse reaction, or communicate an urgent medication recommendation. Repeated practice can increase familiarity and reduce anxiety before students encounter comparable situations clinically.

The finding is that digital learning should be strategically integrated rather than used merely as electronic content delivery. Digital pharmacology resources can provide interactive mechanisms of action, virtual patients, drug databases, clinical calculators, adaptive quizzes, electronic formularies, simulated prescribing systems, and immediate feedback. These resources can support self-directed learning and repeated practice.

However, the educational value of digital learning depends on instructional design. Converting a traditional lecture into a video does not automatically constitute innovation. Effective digital learning should require students to retrieve, apply, compare, predict, explain, or make decisions. Interactive clinical cases and adaptive assessment are therefore likely to be more educationally valuable than passive video consumption.

The fourteenth finding concerns gamification and game-based learning. Game-based approaches can potentially improve engagement, retrieval, knowledge reinforcement, and motivation. They may be particularly useful for learning drug classifications, mechanisms, adverse effects, interactions, and clinical recognition patterns. However, gamification should support educational objectives rather than become an entertainment activity. Competitive elements should be designed carefully to prevent superficial learning and excessive anxiety.

The finding concerns flipped learning. The flipped model can redistribute educational time by moving basic content acquisition outside scheduled sessions and using classroom time for application. This is particularly relevant to pharmacology because classroom time can be used for prescribing exercises, therapeutic calculations, case analysis, evidence appraisal, and discussion rather than repetitive presentation of information.

The finding is that formative feedback should become an explicit educational intervention. Pharmacological reasoning is complex, and students may not recognize why a therapeutic decision is incorrect. Feedback should therefore explain the reasoning process rather than merely identify the correct answer. For example, if a student selects an inappropriate medicine because of renal impairment, feedback should identify the pharmacokinetic principle involved, explain the clinical consequence, and demonstrate how the treatment decision should be revised.

The finding concerns assessment alignment. Educational objectives, teaching methods, learning activities, and assessment should be constructively aligned. If the curriculum states that students should develop prescribing competence but the final examination measures only factual recall, the assessment system undermines the curriculum's stated goals.

A comprehensive assessment strategy should therefore include multiple modalities. Written examinations can evaluate foundational pharmacological knowledge. Clinical vignettes can assess therapeutic reasoning. Prescription-writing exercises can evaluate practical prescribing. OSCEs can assess integrated clinical performance. Critical appraisal assignments can assess EBM competence. Portfolios can document longitudinal development. Oral examinations can evaluate reasoning under questioning.

The finding concerns prescription-writing competence as an observable clinical skill. Prescription writing should be practiced repeatedly rather than treated as an administrative exercise. Students should learn to specify medicine, dose, route, frequency, duration, relevant instructions, and monitoring requirements. They should also recognize the importance of allergy status, contraindications, interactions, renal and hepatic function, patient age, pregnancy status where relevant, and medication reconciliation.

The finding is that medication safety and pharmacovigilance should be integrated across the curriculum. Students should learn to identify preventable medication errors and distinguish them from adverse drug reactions that occur despite appropriate prescribing. They should understand reporting mechanisms, causality assessment, signal detection, and risk minimization. These concepts should be repeatedly reinforced through clinical cases.

The finding concerns antimicrobial stewardship. Antimicrobial pharmacology should be connected to resistance, diagnostic stewardship, microbiological evidence, pharmacokinetic/pharmacodynamic principles, appropriate spectrum, de-escalation, duration, and prevention of unnecessary exposure. Students should understand that individual prescribing decisions have population-level consequences.

The finding concerns polypharmacy and multimorbidity. Traditional pharmacology cases frequently focus on single diseases and single medicines. Modern clinical practice is different. Students should therefore encounter cases involving multiple chronic diseases and multiple medications. Such cases can teach therapeutic prioritization, deprescribing, interaction management, adherence assessment, medication reconciliation, and risk-benefit evaluation.

The finding is the importance of patient-centered pharmacotherapy. Treatment decisions should incorporate patient preferences, values, health literacy, adherence capacity, financial considerations, route preferences, lifestyle, and treatment goals. Students should learn to communicate uncertainty and risk using understandable language. The ability to prescribe correctly but communicate poorly remains an incomplete form of therapeutic competence.

The finding concerns pharmacogenomics and precision medicine. Contemporary pharmacology education should introduce students to genetic determinants of drug response and toxicity. The objective is not to turn all MD students into pharmacogenomics specialists but to establish sufficient conceptual competence to recognize when genetic information may be clinically relevant and when specialized testing or consultation may be appropriate.

The finding concerns clinical decision-support systems. Electronic prescribing systems, interaction databases, dosage calculators, and guideline-integrated tools increasingly influence clinical decisions. Students should learn how to use such systems appropriately while recognizing that decision-support tools can contain incomplete information or generate excessive alerts. Competence therefore requires both technological literacy and clinical judgment.

The finding concerns artificial intelligence in pharmacology education. AI may support personalized explanations, simulated cases, question generation, feedback, literature navigation, and adaptive learning. However, students should be trained to verify AI-generated information and recognize that plausible language does not guarantee pharmacological accuracy. AI should therefore be positioned as an assistive educational resource within a framework of human supervision, evidence verification, and professional accountability.

The finding concerns information literacy. Students are increasingly confronted with an enormous volume of pharmacological information from textbooks, databases, websites, social media, pharmaceutical promotional materials, AI systems, and clinical guidelines. The ability to identify authoritative information is therefore a core professional competence. Students should be trained to prioritize peer-reviewed evidence, authoritative formularies, regulatory information, evidence-based guidelines, systematic reviews, and appropriately designed primary studies.

The finding concerns clinical reasoning. Pharmacological decisions should be incorporated into broader diagnostic and therapeutic reasoning. Students should learn that medication selection is dependent upon the certainty of diagnosis, severity of disease, prognosis, therapeutic goals, competing risks, and patient context. Pharmacology should therefore be integrated into clinical reasoning rather than taught as an independent decision-making system.

The finding is that uncertainty should be explicitly taught. Medical evidence is rarely absolute. Studies have confidence intervals, heterogeneous populations, methodological limitations, and

uncertain external validity. Students should understand that evidence-informed prescribing frequently involves balancing probabilities rather than identifying certainty. Teaching uncertainty can reduce inappropriate confidence and promote safer clinical decision-making.

The finding concerns critical appraisal of pharmaceutical information. Students should be able to identify potential conflicts of interest, industry sponsorship, selective reporting, surrogate endpoints, publication bias, inappropriate subgroup analysis, and exaggerated relative treatment effects. This competence is essential because prescribing decisions can be influenced by commercial communication as well as scientific evidence.

The concerns faculty development. Innovative curricula cannot be sustained if educators lack the pedagogical expertise necessary to implement them. Faculty development should address active learning, EBM instruction, case development, simulation, assessment, feedback, digital teaching, AI literacy, and educational research methodology.

The finding concerns institutional support. Curriculum innovation requires time, infrastructure, educational technology, clinical partnerships, simulation facilities, access to evidence resources, and appropriate recognition of teaching scholarship. Without institutional support, educational innovation may remain dependent on individual faculty enthusiasm and become unsustainable.

The finding concerns educational evaluation. The available literature reveals a substantial imbalance between immediate educational outcomes and meaningful clinical outcomes. The 80-study scoping review found positive results primarily at Kirkpatrick levels 1 and 2 and no level 3 or 4 outcomes. This represents one of the most important research gaps in pharmacology education. Future studies should therefore evaluate whether educational interventions alter prescribing behavior, medication safety, clinical reasoning, and patient outcomes. Longitudinal assessments should examine knowledge retention and transfer after graduation. Multicenter studies should compare educational strategies using validated instruments and standardized competencies.

The finding concerns the need for standardized pharmacological competencies. Existing literature has identified uncertainty regarding precisely which prescribing competencies medical graduates should possess. Universities should therefore collaborate to define minimum graduate competencies in pharmacology, pharmacotherapy, prescribing, medication safety, pharmacovigilance, EBM, and clinical reasoning.

A proposed minimum competency framework should include the following domains: foundational pharmacological science; therapeutic selection; dose individualization; prescription writing; medication reconciliation; adverse drug reaction recognition; drug-interaction management; antimicrobial stewardship; pharmacovigilance; EBM; patient counseling; shared decision-making; interprofessional communication; ethical prescribing; digital literacy; and lifelong therapeutic learning.

The finding concerns progressive complexity. Competence should not be expected to emerge suddenly during the final year of medical education. Instead, competencies should develop through a deliberate progression from simple to complex cases. The first stage may involve individual drug mechanisms. The second may involve treatment of common conditions. The third may involve individualized prescribing. The fourth may involve polypharmacy and multimorbidity. The fifth may involve uncertainty, competing risks, and evidence conflicts. The final stage should involve independent clinical reasoning under supervision.

The finding concerns the role of clinical pharmacologists and pharmacology educators. These professionals can serve as bridges between basic science and clinical medicine. Their contribution should extend beyond classroom teaching to curriculum development, prescribing assessment, medication-safety initiatives, pharmacovigilance education, clinical consultation, and educational research.

The finding is that pharmacy and medical education should interact more closely. Pharmacists contribute specialized knowledge regarding medicine selection, interactions, adherence,

medication-use systems, and safety. Interprofessional learning can help MD students recognize when pharmacist expertise should be sought and how collaborative decision-making can improve medication management.

The finding concerns graduate preparedness. The literature indicating deficiencies among final-year students suggests that universities should not assume that clinical exposure automatically produces prescribing competence. Structured learning objectives and explicit assessment are necessary to ensure that students achieve minimum competencies before graduation.

The finding concerns retention. Immediate post-intervention improvements are insufficient if knowledge and skills disappear rapidly. Educational programmes should therefore use spaced repetition, longitudinal reinforcement, cumulative assessment, and repeated clinical application. Pharmacology concepts should recur across multiple courses rather than being examined once and subsequently abandoned.

The finding is that retrieval practice and repeated application should become central to pharmacology learning. Students should repeatedly retrieve important concepts and apply them to different clinical contexts. This is especially important for high-risk medications, common therapeutic principles, dose calculations, adverse reactions, and emergency pharmacotherapy.

The finding concerns educational personalization. Students enter medical school with different levels of prior knowledge and develop different areas of difficulty. Adaptive digital assessment can identify weaknesses and provide targeted practice. Nevertheless, personalization should complement rather than replace faculty supervision.

The finding concerns equity and accessibility. Digital innovation should not increase educational disparities. Institutions should ensure access to essential learning resources, provide appropriate alternatives when technology is unavailable, and design materials that accommodate diverse learning needs.

The finding concerns global applicability. The principles of pharmacological reasoning, EBM, patient safety, and rational prescribing are internationally transferable, although formularies, regulations, guidelines, and resource availability differ. MD programmes should therefore teach universal principles while ensuring that students understand the therapeutic environment in which they will practice.

The finding is that medical pharmacology should be treated as a patient-safety discipline. Medication-related harm is not simply a clinical problem occurring after graduation; its prevention begins during medical school. Every prescribing exercise, therapeutic case, and assessment represents an opportunity to establish safe professional habits.

The finding concerns ethical responsibility. Physicians possess substantial authority over medication exposure. Students must therefore understand that prescribing carries ethical responsibilities involving autonomy, beneficence, non-maleficence, justice, transparency, and accountability. Evidence-based prescribing should be integrated with patient-centered ethical reasoning.

The finding concerns the need for curricular coherence. Educational innovations are most effective when they form part of a coherent curriculum rather than appearing as isolated activities. A university should therefore map pharmacological competencies across courses, identify where each competency is introduced, reinforced, and assessed, and identify gaps or unnecessary duplication.

The finding concerns constructive alignment. Learning objectives should determine educational activities and assessment. If the intended objective is evidence-informed prescribing, students should be given opportunities to appraise evidence and should be assessed on evidence-informed prescribing. If the objective is medication safety, students should encounter medication-error scenarios and be assessed on their ability to identify and prevent errors.

The finding concerns educational scholarship. Faculty should systematically evaluate innovations rather than simply introducing them. Educational interventions should be described sufficiently clearly to permit replication and should use appropriate outcome measures. Publication of negative or neutral findings is also important to reduce publication bias and provide realistic evidence regarding educational effectiveness.

The finding concerns the importance of longitudinal clinical integration of EBM. The evidence suggests that classroom-based EBM instruction can improve knowledge, but clinically integrated approaches may better support broader competencies. Consequently, EBM should appear repeatedly during pharmacology and clinical rotations in response to authentic therapeutic questions.

The finding is that the strongest conceptual model is multimodal rather than monolithic. No single teaching strategy should dominate the entire pharmacology curriculum. Lectures, cases, problem-based learning, team-based learning, simulation, digital education, experiential learning, EBM exercises, interprofessional education, and independent study each address different educational requirements.

The major finding is that the ultimate outcome of pharmacology education should be defined as evidence-informed therapeutic competence. This competence represents the integrated capacity to understand pharmacological science, identify therapeutic problems, evaluate evidence, select individualized treatment, prescribe safely, monitor outcomes, recognize harm, communicate effectively, collaborate with other professionals, and continuously update knowledge.

On the basis of the synthesized findings, the proposed educational framework can be conceptualized as a progressive six-dimensional model. The first dimension is scientific pharmacology, establishing the biological and mechanistic foundation. The second is pharmacotherapeutic reasoning, translating scientific principles into treatment decisions. The third is Evidence-Based Medicine, enabling students to locate and evaluate external evidence. The fourth is clinical performance, encompassing prescribing, monitoring, medication reconciliation, and patient counseling. The fifth is professional and safety competence, incorporating pharmacovigilance, antimicrobial stewardship, ethical practice, interprofessional collaboration, and medication safety. The sixth is lifelong learning, enabling graduates to respond to therapeutic innovation and continuously changing evidence.

The interaction of these dimensions creates an educational pathway from knowledge to application, application to reasoning, reasoning to evidence-informed decision-making, decision-making to safe clinical performance, and clinical performance to lifelong professional competence. This progression should be explicitly represented in curriculum maps, course objectives, teaching activities, assessment systems, and faculty-development programmes.

The evidence also indicates that the proposed framework should be implemented longitudinally rather than through a single curricular reform event. During the early years of the MD programme, students should establish foundational pharmacological knowledge and basic evidence-appraisal skills. During intermediate years, pharmacology should become increasingly case-based and integrated with organ-system medicine. During clinical years, students should perform supervised prescribing, medication review, pharmacovigilance, and evidence-appraisal activities. During the final phase, assessment should focus on integrated therapeutic competence and preparedness for safe prescribing.

An additional research implication is the need for a more sophisticated educational evidence base. Future investigations should compare integrated versus isolated pharmacology education; determine the relative effectiveness of different active-learning strategies; evaluate longitudinal retention; examine transfer into clinical settings; assess interprofessional interventions; evaluate simulation and digital learning; and investigate how AI affects pharmacological learning and clinical

reasoning. Studies should use validated outcome measures, appropriate comparison groups, effect sizes, delayed assessments, and, where feasible, behavioral and patient-level outcomes.

The existing literature provides an encouraging foundation but also demonstrates that the field remains methodologically immature. The consistent presence of positive short-term educational outcomes suggests that pharmacology education can be improved substantially through structured intervention. However, the absence of sufficient evidence at higher Kirkpatrick levels means that educational researchers should resist overclaiming the clinical effectiveness of individual pedagogical approaches. The appropriate conclusion is that innovative and integrated teaching strategies show promise, while rigorous longitudinal evaluation remains necessary.

The conceptual synthesis therefore establishes several overarching conclusions. Medical pharmacology education should be clinically oriented, longitudinally integrated, competency-based, evidence-informed, patient-centered, technologically supported, and continuously evaluated. Pharmacology should no longer be regarded as an isolated body of preclinical information but as an essential component of clinical decision-making and patient safety. Pharmacotherapy should be taught as an applied reasoning process. Clinical pharmacology should provide the bridge between mechanisms and patient-specific treatment. EBM should provide the epistemic foundation for evaluating therapeutic alternatives. Innovative educational strategies should provide the learning environment in which students repeatedly practice these competencies.

The resulting educational philosophy is fundamentally different from a traditional content-delivery model. Its central question is no longer “How much pharmacology can students remember?” but “Can students use pharmacological knowledge to make safe, rational, evidence-informed decisions for individual patients?” This shift represents the principal research finding of the present conceptual analysis.

The proposed framework consequently defines successful medical pharmacology education through observable performance. A successful MD graduate should be able to explain the scientific basis of drug action; identify appropriate therapeutic objectives; select medicines using evidence and patient-specific information; calculate and prescribe appropriate doses; recognize contraindications and interactions; monitor efficacy and safety; detect and report adverse drug reactions; apply antimicrobial stewardship principles; critically appraise evidence; communicate treatment decisions; collaborate with pharmacists and other healthcare professionals; use digital and AI-supported resources critically; and recognize when new evidence requires reconsideration of established practice.

In this context, educational excellence becomes inseparable from clinical safety. Improving pharmacology education is therefore not merely a pedagogical exercise. It is an institutional responsibility to future patients and healthcare systems. The preparation of physicians capable of safe and rational medicine use requires deliberate curricular design, sustained faculty development, appropriate assessment, meaningful clinical integration, and systematic educational evaluation.

The research and findings support the implementation of a comprehensive, longitudinal, competency-based model integrating medical pharmacology, pharmacotherapy, clinical pharmacology, Evidence-Based Medicine, active learning, case-based education, problem-based learning, team-based learning, simulation, digital education, interprofessional learning, formative feedback, prescribing practice, pharmacovigilance, medication safety, and lifelong learning. The evidence does not support a simplistic replacement of traditional teaching with one “innovative” method. Rather, it supports a carefully designed educational ecosystem in which different strategies are deliberately selected according to specific learning objectives.

The educational product should therefore be a physician who does not merely know medicines but understands how to use them responsibly. Such a physician can integrate scientific evidence

with clinical circumstances, patient preferences, professional expertise, and safety considerations. This represents the essential transition from pharmacological knowledge to therapeutic competence, and it constitutes the central foundation of a modern university-based medical pharmacology curriculum for MD students.

The synthesis indicates that the central challenge in contemporary pharmacology education is not the absence of pharmacological information but the difficulty of converting large volumes of information into durable, clinically transferable competence. The literature consistently demonstrates a movement toward integrated, active, learner-centered education. Recent pharmacology scholarship specifically identifies active learning, case-based learning, problem-based learning, team-based learning, personalized learning, and technology-supported engagement as important directions for curriculum development.

Medical Pharmacology and Clinical Pharmacology for MD Medical Students

Medical pharmacology and clinical pharmacology represent core disciplines within undergraduate medical education, providing the essential scientific and clinical foundations for rational drug therapy and patient-centered pharmacotherapeutic decision-making. In contemporary medical education, rapid advances in biomedical sciences, molecular medicine, pharmacogenomics, and therapeutic technologies necessitate the continuous improvement and modernization of pharmacology curricula. The improvement of the learning course in medical pharmacology and clinical pharmacology for MD students is therefore a critical academic priority aimed at enhancing the quality of medical training, ensuring safe prescribing practices, and strengthening the integration between basic biomedical knowledge and clinical practice.

The conceptual plan for the improvement of this course focuses on strengthening theoretical depth, promoting clinical relevance, incorporating innovative teaching methodologies, and aligning the curriculum with international standards of medical education. The revised course design seeks to foster analytical thinking, evidence-based therapeutic decision-making, and professional competencies necessary for modern physicians.

Academic Goals of the Course Improvement

The improvement strategy for the learning course aims to enhance the educational effectiveness of pharmacology instruction by reinforcing the integration of basic pharmacological sciences with clinical pharmacotherapy. The improved curriculum is designed to support the development of advanced competencies in rational prescribing, drug safety evaluation, therapeutic monitoring, and individualized treatment strategies.

A major objective of the course enhancement is to shift the traditional teaching paradigm from memorization of drug lists toward a deeper conceptual understanding of pharmacological mechanisms, clinical reasoning, and patient-oriented pharmacotherapy. This approach ensures that future physicians acquire not only knowledge of pharmacological agents but also the capacity to apply this knowledge effectively in complex clinical contexts.

Conceptual Framework for Course Improvement

The conceptual framework of the improved course is structured around four interconnected academic pillars.

The first pillar focuses on foundational pharmacological sciences, including molecular pharmacology, pharmacokinetics, and pharmacodynamics. Strengthening these theoretical foundations allows students to understand the biological mechanisms underlying drug action and therapeutic effects.

The second pillar emphasizes system-based pharmacology, in which pharmacological agents are studied in relation to specific physiological systems and disease processes. This structure promotes a clinically integrated understanding of pharmacotherapy.

The third pillar centers on clinical pharmacology and rational therapeutics, including drug selection, dose optimization, therapeutic drug monitoring, and evidence-based prescribing practices.

The fourth pillar incorporates innovative and future-oriented pharmacology, including pharmacogenetics, personalized medicine, biologic therapies, and emerging pharmacological technologies.

Through the integration of these conceptual domains, the improved course provides a comprehensive educational framework that bridges fundamental pharmacological science with clinical medical practice.

Curriculum Structure and Content Enhancement

The improved curriculum includes several thematic modules designed to progressively develop pharmacological knowledge and clinical competencies.

The introductory component of the course focuses on general principles of pharmacology, including drug classification, mechanisms of drug action, receptor pharmacology, and the scientific basis of pharmacotherapy. Students are introduced to the processes of drug discovery, clinical trials, regulatory approval, and post-marketing surveillance.

The next component addresses pharmacokinetic principles, including drug absorption, distribution, metabolism, and elimination. Emphasis is placed on understanding pharmacokinetic variability, therapeutic drug monitoring, and the impact of physiological and pathological conditions on drug disposition.

Pharmacodynamic principles are then explored in detail, including receptor binding, dose–response relationships, signal transduction mechanisms, therapeutic index, drug potency, and efficacy. These concepts form the scientific basis for rational therapeutic decision-making.

System-based pharmacology represents a major component of the course. Within this framework, students study pharmacological treatments related to major organ systems, including the cardiovascular system, central nervous system, respiratory system, gastrointestinal system, endocrine system, and immune system. Each system-based module integrates pathophysiological mechanisms with pharmacological interventions, allowing students to develop a clinically oriented understanding of drug therapy.

A dedicated section of the curriculum focuses on antimicrobial pharmacology and chemotherapy, addressing the mechanisms of action of antibiotics, antiviral agents, antifungal drugs, and antiparasitic medications. Special attention is given to antimicrobial resistance, rational antibiotic prescribing, and global public health implications.

Clinical pharmacology represents a central component of the improved course. Students learn principles of rational prescribing, therapeutic guidelines, drug selection strategies, and patient-specific dose adjustment. The course also addresses issues such as polypharmacy, drug–drug interactions, and medication management in special populations, including pediatric, geriatric, and pregnant patients.

Drug safety and pharmacovigilance constitute another critical component of the curriculum. Students are trained to recognize adverse drug reactions, identify medication errors, and understand the importance of pharmacovigilance systems in ensuring medication safety at both national and international levels.

The course also integrates emerging areas of pharmacological science, including pharmacogenomics, targeted therapies, biologic drugs, monoclonal antibodies, and

nanopharmacology. These topics provide students with insights into the future directions of pharmacotherapy and personalized medicine.

Innovative Teaching and Learning Strategies

The improvement of the pharmacology course involves the incorporation of modern pedagogical strategies that enhance student engagement and clinical reasoning. Traditional lectures are complemented by interactive teaching methods such as problem-based learning, case-based discussions, and small-group seminars.

Clinical case simulations and scenario-based learning exercises allow students to apply pharmacological knowledge in realistic clinical contexts. These activities strengthen diagnostic reasoning and therapeutic decision-making skills.

Digital educational technologies, including virtual pharmacology laboratories, online pharmacological databases, and e-learning platforms, are integrated into the course to support independent learning and facilitate access to updated pharmacological information.

Interdisciplinary teaching approaches are also encouraged, promoting collaboration between pharmacology faculty and clinical departments such as internal medicine, cardiology, infectious diseases, and oncology.

Improved Teaching and Learning Methods in Medical Pharmacology and Clinical Pharmacology for MD Medical Students

The improvement of the learning course in Medical Pharmacology and Clinical Pharmacology requires the implementation of diverse, student-centered, and clinically oriented teaching and learning methods. Modern medical education emphasizes active learning, integration of theoretical knowledge with clinical practice, and the development of critical thinking and decision-making skills. Therefore, a combination of traditional and innovative pedagogical approaches should be employed to ensure comprehensive understanding and practical application of pharmacological principles.

One of the core teaching strategies is the use of interactive lectures. These lectures should not be limited to passive knowledge transmission but should incorporate discussion, questioning, and problem-solving activities. The interactive format allows students to engage with pharmacological concepts actively, facilitating deeper understanding of drug mechanisms, pharmacokinetic processes, and therapeutic applications.

Another essential method is case-based learning (CBL). In this approach, pharmacological knowledge is presented through clinical cases that simulate real patient scenarios. Students analyze symptoms, review diagnostic information, and determine appropriate pharmacotherapeutic interventions. Case-based learning strengthens clinical reasoning and helps students apply pharmacological theory to practical medical decision-making.

Problem-based learning (PBL) represents an additional important pedagogical strategy. In PBL sessions, small groups of students are presented with complex clinical problems that require independent research, collaborative discussion, and evidence-based solutions. This method promotes self-directed learning, critical analysis, and the integration of pharmacology with other biomedical sciences.

Small-group seminars and discussions are also highly effective in pharmacology education. These sessions allow students to explore complex pharmacological topics in depth, discuss recent research findings, and engage in scientific dialogue with instructors and peers. Seminar-based learning encourages analytical thinking and supports the development of communication skills.

The incorporation of clinical pharmacology simulations provides students with opportunities to practice therapeutic decision-making in controlled educational environments. Simulation-based exercises may include virtual patients, prescribing simulations, or computerized pharmacotherapy

scenarios. Such activities help students develop competence in drug selection, dosage calculation, and management of adverse drug reactions.

Laboratory demonstrations and practical sessions also play an important role in pharmacology education. These activities may include experimental demonstrations of drug effects, pharmacokinetic modeling exercises, or interpretation of pharmacological data. Practical sessions enhance students' understanding of pharmacological mechanisms and experimental methods used in drug research.

Another recommended teaching method is integrated interdisciplinary teaching. Collaboration between pharmacology faculty and clinical departments enables students to observe how pharmacological principles are applied in real medical practice. Joint teaching sessions with specialists from cardiology, infectious diseases, endocrinology, or oncology can significantly strengthen the clinical relevance of pharmacology education.

The use of digital learning technologies further enhances the learning process. Online educational platforms, pharmacology databases, electronic drug formularies, and multimedia resources allow students to access up-to-date pharmacological information and support independent learning. Virtual learning environments can also facilitate quizzes, discussion forums, and interactive pharmacology modules.

The research-oriented learning should be encouraged. Students may be involved in literature reviews, pharmacological research projects, or critical analysis of clinical trial data. Exposure to research methodology helps students develop scientific thinking and prepares them for evidence-based medical practice.

The effective teaching and learning of medical pharmacology and clinical pharmacology require a multifaceted educational approach that combines interactive lectures, case-based learning, problem-based learning, simulations, interdisciplinary teaching, and digital educational resources. The integration of these methods supports the development of competent medical graduates capable of applying pharmacological knowledge responsibly and effectively in clinical practice.

Concept for Improving Pharmacology Teaching: Within the Learning Course of Medical Pharmacology and Clinical Pharmacology for MD Medical Students

The improvement of pharmacology teaching within the medical curriculum represents an essential component of modern medical education. Pharmacology is a foundational biomedical discipline that directly influences clinical decision-making, therapeutic safety, and patient outcomes. Consequently, the development of an effective teaching concept requires a systematic transformation of traditional educational approaches toward more integrated, clinically oriented, and competency-based learning models.

The conceptual framework for improving pharmacology teaching is based on several strategic academic principles: integration of basic and clinical sciences, development of rational prescribing competencies, and incorporation of innovative educational methodologies, and alignment with international standards of medical education. These principles ensure that pharmacology instruction contributes not only to theoretical knowledge acquisition but also to the development of professional competencies required for safe and effective pharmacotherapy.

A central element of the improvement concept is the integration of pharmacology with clinical disciplines. Pharmacology teaching should not be presented as an isolated theoretical subject but rather as a discipline closely connected to clinical medicine. This integration can be achieved through system-based teaching models in which pharmacological agents are studied in the context of specific disease processes and clinical management strategies. By linking pharmacological mechanisms with pathophysiology and therapeutic guidelines, students develop a deeper understanding of the practical application of pharmacological knowledge.

Another important aspect of the improvement concept is the transition from memorization-based learning to mechanism-based and problem-oriented education. Traditional pharmacology education often emphasizes the memorization of extensive drug lists and classifications. However, contemporary educational models prioritize understanding of drug mechanisms, pharmacokinetic and pharmacodynamic principles, and clinical reasoning processes. Through this approach, students learn to analyze therapeutic options rather than simply recall pharmacological information.

The concept also emphasizes the development of rational prescribing competencies. Future physicians must acquire the ability to select appropriate medications, determine optimal dosages, recognize potential drug interactions, and monitor therapeutic outcomes. Educational activities should therefore include clinical case analysis, therapeutic decision-making exercises, and guideline-based pharmacotherapy discussions. Such training supports the formation of responsible prescribing practices and enhances patient safety.

A further dimension of the improvement concept involves the integration of pharmacovigilance and drug safety education. Medical students must understand the mechanisms underlying adverse drug reactions, drug toxicity, and medication errors. Teaching should include systematic training in the identification, reporting, and prevention of adverse drug reactions, as well as the principles of national and international pharmacovigilance systems.

The incorporation of modern scientific developments in pharmacology also represents a key element of the conceptual framework. Advances in pharmacogenomics, molecular pharmacology, targeted therapies, and biologic drugs are transforming contemporary pharmacotherapy. Therefore, the pharmacology curriculum should include updated content reflecting these developments and highlight the role of personalized medicine in optimizing therapeutic outcomes. Another significant component of the improvement concept is the implementation of innovative pedagogical methods. Active learning strategies such as case-based learning, problem-based learning, simulation-based training, and interactive seminars promote deeper cognitive engagement and enhance knowledge retention. These methods encourage students to participate actively in the learning process and facilitate the development of analytical and clinical reasoning skills.

The concept further recommends the use of digital technologies and modern educational resources. Electronic pharmacology databases, online drug formularies, virtual learning platforms, and clinical decision-support tools provide students with access to current pharmacological information and support independent learning. Digital platforms can also facilitate formative assessment, collaborative learning, and interactive educational modules.

Interdisciplinary collaboration represents another important component of the conceptual improvement strategy. Close cooperation between pharmacology departments and clinical specialties allows students to observe the real-world application of pharmacological principles. Joint teaching activities, clinical demonstrations, and interdisciplinary seminars enhance the clinical relevance of pharmacology education and strengthen the connection between theoretical knowledge and patient care.

Finally, continuous curriculum evaluation and educational quality assurance should be implemented to maintain the effectiveness of pharmacology teaching. Regular feedback from students, faculty members, and healthcare practitioners can identify strengths and weaknesses within the curriculum and guide further improvements. Educational outcomes should also be periodically assessed to ensure alignment with the competencies required for modern medical practice.

The concept for improving pharmacology teaching is based on a comprehensive educational strategy that integrates scientific innovation, clinical relevance, and modern pedagogical approaches. By strengthening the connection between pharmacological science and clinical

practice, this conceptual framework supports the development of competent physicians who are capable of applying pharmacological knowledge responsibly and effectively in patient-centered healthcare.

Assessment and Evaluation Strategies

The improved course incorporates a comprehensive assessment system designed to evaluate both theoretical knowledge and clinical competence. Written examinations remain an important component of student evaluation, including multiple-choice questions, short-answer questions, and problem-solving exercises.

Objective Structured Practical Examinations (OSPE) and clinical pharmacology case analyses are introduced to assess students' ability to apply pharmacological knowledge in practical clinical scenarios.

Oral examinations, seminar presentations, and research-based assignments provide additional opportunities for students to demonstrate analytical thinking and scientific reasoning.

Continuous formative assessment is implemented throughout the course to monitor student progress and provide constructive feedback that supports learning development.

Expected Educational Outcomes

The improved learning course aims to produce medical graduates who possess a strong understanding of pharmacological principles and the ability to apply these principles effectively in clinical practice. Students completing the course are expected to demonstrate competencies in rational prescribing, safe medication management, and evidence-based pharmacotherapy.

Graduates will be capable of critically evaluating pharmacological research, interpreting clinical guidelines, and integrating pharmacological knowledge into comprehensive patient care strategies.

Furthermore, the improved course prepares future physicians to adapt to the rapidly evolving landscape of pharmacological science, ensuring lifelong learning and professional development in the field of clinical therapeutics.

Syllabus Enhancement Strategies: For the Learning Course of Medical Pharmacology and Clinical Pharmacology for MD Medical Students

The continuous enhancement of the syllabus in Medical Pharmacology and Clinical Pharmacology is fundamental for maintaining the academic relevance, scientific rigor, and clinical applicability of pharmacology education within the MD curriculum. As pharmacological science evolves rapidly due to advances in molecular biology, pharmacogenomics, biotechnology, and therapeutic innovations, the syllabus must be regularly updated to reflect contemporary developments and global standards in medical education.

Syllabus enhancement strategies aim to strengthen the alignment between learning objectives, teaching methodologies, clinical competencies, and assessment systems, thereby ensuring that pharmacology education prepares medical students for rational and safe pharmacotherapeutic practice.

Alignment of the Syllabus with Competency-Based Medical Education

One of the primary strategies for syllabus improvement is the alignment with competency-based medical education (CBME) frameworks. The pharmacology syllabus should be designed to support the development of core medical competencies such as rational prescribing, clinical decision-making, patient safety, and evidence-based pharmacotherapy.

Learning outcomes should clearly define the knowledge, skills, and professional attitudes that students are expected to achieve. These outcomes should correspond to internationally recognize medical education standards and professional competency frameworks.

Integration of Basic and Clinical Pharmacology

Another important strategy involves strengthening the integration between basic pharmacology and clinical pharmacology within the syllabus structure. Rather than presenting pharmacological concepts in isolation, the syllabus should integrate molecular mechanisms of drug action with clinical therapeutic applications.

A system-based organizational structure is recommended, where pharmacological agents are studied in relation to specific physiological systems and disease conditions. This approach allows students to connect pharmacological mechanisms with pathophysiology, diagnosis, and therapeutic management.

Inclusion of Emerging and Innovative Areas of Pharmacology

The syllabus should incorporate contemporary developments in pharmacological science, including:

- Pharmacogenomics and personalized medicine
- Biologic therapies and monoclonal antibodies
- Targeted molecular therapies in oncology
- Nanomedicine and advanced drug delivery systems
- Immunopharmacology and immunotherapy
- Advances in antimicrobial pharmacology and resistance mechanisms

Incorporating these topics ensures that students remain informed about modern therapeutic innovations and future directions in pharmacology.

Strengthening Clinical Relevance and Therapeutic Application

To improve clinical competence, the syllabus should place greater emphasis on clinical pharmacology and rational pharmacotherapy. Topics should include therapeutic guidelines, drug selection strategies, dose individualization, therapeutic drug monitoring, and management of drug interactions.

Special attention should also be given to pharmacotherapy in special patient populations, including pediatric, geriatric, pregnant, and critically ill patients. These areas are essential for preparing students to manage diverse clinical situations.

Integration of Drug Safety and Pharmacovigilance Education

Modern pharmacology education must emphasize the importance of drug safety and pharmacovigilance. The enhanced syllabus should include systematic training in the identification, reporting, and prevention of adverse drug reactions, medication errors, and drug toxicity.

Students should also be introduced to national and international pharmacovigilance systems and the regulatory frameworks governing drug safety monitoring.

Incorporation of Active Learning Components

An effective pharmacology syllabus should integrate **active learning activities** such as clinical case discussions, pharmacotherapy workshops, and problem-based learning sessions. These activities should be embedded within the syllabus structure and linked to specific learning objectives.

By incorporating active learning strategies, the syllabus promotes deeper understanding of pharmacological concepts and encourages the development of analytical and clinical reasoning skills.

Integration of Digital Educational Resources

The enhanced syllabus should incorporate the use of digital learning tools and educational technologies, including pharmacology databases, electronic drug formularies, virtual learning platforms, and simulation-based educational resources.

Digital technologies support independent learning, facilitate access to updated pharmacological information, and enable interactive educational experiences.

Continuous Review and Quality Assurance

Finally, an effective syllabus enhancement strategy requires continuous review and quality assurance mechanisms. Periodic evaluation of course content, teaching methods, and assessment strategies should be conducted to ensure alignment with evolving scientific knowledge and healthcare needs.

Feedback from students, educators, and clinical practitioners should be incorporated into the revision process to maintain the relevance and effectiveness of the pharmacology curriculum.

The enhancement of the pharmacology syllabus for MD medical students represents a dynamic and ongoing academic process. Through the integration of competency-based education, clinical relevance, scientific innovation, and modern pedagogical approaches, the enhanced syllabus can significantly improve pharmacology education and better prepare future physicians for responsible and evidence-based pharmacotherapeutic practice.

Research Findings

The synthesized evidence supports the following principal research findings.

First, medical pharmacology education is most educationally meaningful when foundational science is explicitly connected with therapeutic decisions.

Second, competency-based education provides a suitable organizing principle because pharmacological competence includes knowledge, reasoning, practical prescribing, communication, safety, evidence appraisal, and professional judgment.

Third, EBM should be longitudinally embedded in pharmacology and pharmacotherapy rather than taught as an isolated methodological subject. Students should repeatedly formulate therapeutic questions, retrieve evidence, critically appraise studies, and apply findings to patient cases.

Fourth, no single educational strategy can be considered universally optimal. The evidence favors appropriately designed combinations of active learning, cases, problem-based learning, team-based learning, simulation, digital learning, and targeted lectures.

Fifth, clinical integration appears particularly important for transferring EBM knowledge and pharmacological reasoning into meaningful clinical competence.

Sixth, prescribing education should begin early and continue longitudinally. Students need repeated practice rather than a single prescribing course.

Seventh, simulation and digital learning can provide valuable opportunities for repeated therapeutic practice, although they should be integrated with authentic clinical and interprofessional experiences.

Eighth, assessment represents a critical driver of learning. If universities want students to develop prescribing competence, critical appraisal, and therapeutic reasoning, those capabilities must be directly assessed.

Ninth, formative feedback should become a routine element of pharmacology teaching because students need repeated opportunities to identify and correct errors in reasoning.

Tenth, pharmacology curricula should explicitly incorporate medication safety, pharmacovigilance, antimicrobial stewardship, polypharmacy, deprescribing, individualized therapy, and ethical prescribing.

Eleventh, interprofessional learning can strengthen understanding of medication-related responsibilities and improve collaborative competence.

Twelfth, future research should prioritize high-quality longitudinal studies capable of determining whether educational innovations change prescribing behavior and patient-related outcomes rather than relying predominantly on immediate examination scores or satisfaction measures.

Proposed Conceptual Educational Framework

The proposed framework can be represented as a six-layer educational architecture.

Layer 1: Scientific foundation. Students develop knowledge of pharmacodynamics, pharmacokinetics, receptors, molecular mechanisms, dose-response relationships, adverse drug reactions, interactions, pharmacogenomics, and toxicology.

Layer 2: Therapeutic reasoning. Students connect pharmacological principles with diagnosis, pathophysiology, therapeutic objectives, treatment alternatives, contraindications, and patient-specific characteristics.

Layer 3: Evidence integration. Students formulate clinical questions, search biomedical databases, evaluate study design and bias, interpret treatment effects, assess applicability, and integrate evidence into decisions.

Layer 4: Clinical performance. Students prescribe, calculate doses, monitor treatment, identify adverse reactions, conduct medication reconciliation, communicate with patients, and respond to therapeutic problems.

Layer 5: Professional and safety competence. Students develop pharmacovigilance, ethical prescribing, antimicrobial stewardship, interprofessional communication, patient-safety, and accountability competencies.

Layer 6: Continuous learning. Graduates develop the capacity to update therapeutic decisions as evidence, guidelines, technologies, and patient circumstances change.

This framework creates a progression from knowledge → application → evidence appraisal → clinical performance → professional responsibility → lifelong learning.

Suggestions

The conceptual plan for improving the learning course in medical pharmacology and clinical pharmacology represents a strategic academic initiative aimed at modernizing pharmacology education within the MD curriculum. By integrating foundational pharmacological science with clinical application, innovative teaching methodologies, and contemporary therapeutic developments, the improved course provides a comprehensive educational framework for the training of competent and responsible physicians.

The modernization of pharmacology education ultimately contributes to improved healthcare outcomes by ensuring that medical graduates possess the knowledge, skills, and professional judgment necessary for safe and effective pharmacotherapy in clinical practice.

The continuous improvement of the learning course in medical pharmacology and clinical pharmacology is essential to ensure that medical graduates possess the competencies required for safe, rational, and evidence-based pharmacotherapy. Based on contemporary trends in medical education and pharmacological science, several strategic recommendations can be proposed to enhance the academic quality, pedagogical effectiveness, and clinical relevance of the course.

It is recommended to strengthen the integration between basic pharmacology and clinical medicine. Pharmacological teaching should be closely linked with clinical disciplines such as

internal medicine, cardiology, infectious diseases, endocrinology, and oncology. This integration facilitates a deeper understanding of the therapeutic applications of drugs and enables students to connect theoretical pharmacological concepts with real clinical scenarios.

The curriculum should place greater emphasis on rational prescribing and therapeutic decision-making. Instead of focusing primarily on memorization of drug classifications, the course should encourage students to analyze clinical cases, evaluate treatment guidelines, and select the most appropriate pharmacological interventions based on patient-specific factors.

The incorporation of modern teaching methodologies is strongly recommended. Interactive lectures, case-based learning, problem-based learning, and small-group discussions enhance critical thinking and promote active student participation. Simulation-based pharmacology exercises and clinical scenario analyses can further strengthen the development of clinical reasoning skills.

Greater attention should be given to drug safety and pharmacovigilance education. Students should be trained to recognize adverse drug reactions, understand mechanisms of drug toxicity, and apply strategies for preventing medication errors. Familiarity with pharmacovigilance systems and reporting procedures is essential for responsible medical practice.

The curriculum should include expanded coverage of pharmacogenetics and personalized medicine. Genetic variability significantly influences drug metabolism, efficacy, and toxicity. Understanding pharmacogenomic principles will enable future physicians to tailor pharmacotherapy according to individual patient characteristics and improve therapeutic outcomes.

The course should incorporate digital and technological learning resources. Access to pharmacological databases, electronic drug formularies, clinical decision-support systems, and e-learning platforms can support independent learning and provide students with up-to-date pharmacological information.

It is recommended to strengthen interdisciplinary collaboration in pharmacology teaching. Cooperation between pharmacology departments and clinical faculty members allows students to observe the practical implementation of pharmacological principles in patient care and reinforces the clinical relevance of pharmacology education.

The implementation of diverse and competency-based assessment methods is encouraged. In addition to traditional written examinations, assessment strategies such as Objective Structured Practical Examinations (OSPE), clinical case analysis, and oral presentations should be utilized to evaluate both theoretical knowledge and applied pharmacological skills.

Finally, continuous curriculum evaluation and quality assurance mechanisms should be established. Regular feedback from students, faculty members, and clinical practitioners can help identify areas for improvement and ensure that the pharmacology curriculum remains aligned with evolving scientific knowledge and healthcare needs.

The successful improvement of the learning course in medical pharmacology and clinical pharmacology requires a comprehensive educational strategy that integrates modern scientific advances, innovative teaching methods, and strong clinical orientation. Implementing these recommendations will contribute to the development of competent physicians capable of delivering safe, effective, and patient-centered pharmacotherapy.

The major finding is that pharmacology should be conceptualized as a longitudinal clinical competency rather than a single preclinical subject. Students should encounter pharmacological reasoning repeatedly throughout medical education. Early instruction should establish mechanisms and foundational principles; intermediate instruction should emphasize therapeutic selection and clinical cases; and advanced clinical education should require individualized prescribing, monitoring, evidence appraisal, medication reconciliation, and management of adverse drug reactions.

The finding concerns integration between pharmacology and pharmacotherapy. Students should move systematically from “What does this drug do?” toward “Which treatment should be selected for this patient, why, at what dose, for how long, how should it be monitored, and what evidence supports the decision?” This transition represents a fundamental shift from declarative knowledge toward therapeutic reasoning.

The finding concerns competency-based education. Pharmacology competencies should be explicit, observable, progressively developed, and assessable. A proposed competency structure includes six domains: pharmacological knowledge; therapeutic reasoning; prescribing and medication management; medication safety and pharmacovigilance; EBM and information literacy; and professional communication and interprofessional collaboration.

The finding is that EBM should be embedded directly into pharmacological cases. Students should not learn EBM exclusively through isolated lectures. Instead, each major therapeutic module should contain clinically meaningful questions requiring literature retrieval and appraisal. For example, students might compare first-line therapies for hypertension, evaluate evidence supporting a new anticoagulant, assess adverse-event differences between therapies, or determine whether a clinical guideline applies to an older patient with renal impairment.

Evidence indicates that EBM teaching improves aspects of learner competency, but no single educational modality has demonstrated universal superiority. Therefore, universities should avoid methodological absolutism. The most defensible approach is a blended EBM strategy combining brief foundational instruction, guided critical appraisal, clinical cases, digital resources, journal clubs, small-group discussion, and bedside or clinic-based questions.

The finding is that active learning is particularly suitable for pharmacology. Pharmacological concepts frequently require students to integrate mechanisms, disease processes, patient characteristics, and therapeutic objectives. Passive exposure can produce superficial familiarity, whereas active application requires students to retrieve, compare, explain, justify, and revise their reasoning.

Evidence from pharmacology education supports combinations of pedagogical approaches. A network meta-analysis of 150 studies involving more than 21,000 students found favorable performance or satisfaction outcomes associated with several active-learning strategies, particularly combinations of problem-based and case-based learning, team-based learning, and flipped learning. These findings support multimodal rather than single-method teaching.

The finding is that clinical cases should become the principal bridge between pharmacological science and clinical practice. A high-quality pharmacology case should require students to identify a therapeutic objective, consider patient-specific variables, select among treatment alternatives, justify the choice using pharmacological principles and evidence, prescribe appropriately, and establish a monitoring plan.

Case design should progressively increase complexity. Early cases can involve straightforward dose-response reasoning. Later cases should introduce renal impairment, hepatic dysfunction, polypharmacy, pregnancy, advanced age, genetic variation, drug interactions, adherence problems, therapeutic failure, adverse reactions, and competing clinical priorities. This progression mirrors real clinical decision-making.

The finding is that prescribing education should be explicitly incorporated into pharmacology. Evidence from a large scoping review shows extensive use of e-learning, case-based, experiential, and interprofessional interventions to improve pharmacological knowledge and prescribing skills, but also reveals a shortage of evidence demonstrating higher-level effects on real clinical behavior. This gap should become a priority for future educational research.

The finding concerns simulation. Simulation allows students to practice medication-related decisions without exposing patients to risk. Virtual patients, electronic prescribing simulations,

medication-ordering exercises, adverse-reaction scenarios, and clinical decision-support simulations can reproduce many aspects of contemporary therapeutic practice.

Digital simulation literature indicates potential improvements in knowledge, confidence, and satisfaction, while also identifying limitations concerning polypharmacy and interprofessional integration. Therefore, simulation should evolve from isolated drug-identification exercises toward complex patient-centered therapeutic scenarios.

The finding is that interprofessional education should be integrated into pharmacology curricula. Medical students should understand that medication safety depends on coordinated professional activity. Collaborative cases involving physicians, pharmacists, nurses, and other professionals can demonstrate the multiple points at which medication errors occur and the mechanisms by which they can be prevented.

The finding concerns assessment. The assessment system should correspond directly to the educational philosophy. Knowledge can be assessed through appropriately designed written examinations, but prescribing competence requires performance-based assessment. Students should therefore be evaluated using prescription-writing tasks, clinical vignettes, OSCE stations, medication-review exercises, critical appraisal tasks, oral therapeutic reasoning, and longitudinal portfolios.

The finding concerns formative feedback. Pharmacological competence is unlikely to develop through assessment alone. Students require repeated opportunities to receive feedback on their reasoning. Feedback should identify the clinical decision, the underlying pharmacological principle, the evidence supporting or contradicting the decision, and the specific action required for improvement.

The finding concerns personalized learning. Students differ in their prior knowledge, cognitive strategies, learning pace, and areas of difficulty. Digital diagnostic assessments and adaptive educational resources can identify individual knowledge gaps. Personalized learning should, however, remain integrated with faculty guidance rather than becoming an entirely automated process.

The finding concerns faculty development. Curriculum reform cannot succeed simply by changing course documents. Faculty members require preparation in active learning, case construction, EBM instruction, assessment design, feedback, simulation facilitation, digital pedagogy, and educational scholarship. Faculty workload and institutional incentives must also recognize educational innovation.

The finding concerns AI. AI-enabled tools can support personalized explanations, question generation, simulated clinical conversations, feedback, and educational content development. Nevertheless, AI should be treated as an assistive technology rather than an epistemic authority. Students must verify AI-generated pharmacological information against authoritative references and recognize that an apparently plausible recommendation may be inaccurate or contextually inappropriate. Academic integrity, privacy, transparency, and professional accountability should be embedded in AI-related curriculum policies.

The finding is that educational outcomes should be evaluated longitudinally. Existing literature frequently concentrates on knowledge, confidence, and satisfaction, while fewer studies assess behavioral or patient-level outcomes. Universities should therefore evaluate whether educational interventions improve prescribing performance, evidence use, medication-error recognition, clinical reasoning, and sustained competence.

CONCLUSION

- Medical pharmacology education should be fundamentally reoriented from predominantly information-transmission models toward integrated, competency-based, clinically relevant, and evidence-informed education. The increasing complexity of pharmacotherapy makes it

impossible for MD students to rely exclusively on memorization of drug classifications and mechanisms. Future physicians require the capacity to interpret pharmacological information, evaluate evidence, individualize therapy, prescribe safely, monitor treatment, recognize medication-related harm, communicate therapeutic decisions, and continuously update their knowledge.

- The proposed framework integrates medical pharmacology, pharmacotherapy, and clinical pharmacology across the MD curriculum while embedding EBM, active learning, clinical cases, simulation, digital technologies, interprofessional education, formative feedback, and performance-based assessment. Such integration can create a coherent educational trajectory extending from fundamental pharmacological science to authentic clinical decision-making.
- The available literature does not justify declaring a single teaching strategy superior in all educational contexts. Instead, the evidence supports carefully designed multimodal and longitudinal approaches adapted to learning objectives, student needs, institutional resources, and clinical environments. EBM should similarly be taught through repeated clinical application rather than isolated theoretical instruction.
- The quality of pharmacology education should be judged not simply by how much students remember, but by whether they can make scientifically justified, patient-centered, safe, ethical, and evidence-informed therapeutic decisions. Universities should therefore treat pharmacology education as a core component of clinical competence and patient safety rather than as an isolated preclinical discipline.

RECOMMENDATIONS

- Establish longitudinal pharmacology curricula extending from early foundational science through clinical clerkships.
- Integrate pharmacology, pharmacotherapy, and clinical pharmacology rather than teaching them as disconnected subjects.
- Embed EBM throughout pharmacology education, using authentic therapeutic questions and clinical cases.
- Develop explicit pharmacological competencies covering knowledge, therapeutic reasoning, prescribing, medication safety, evidence appraisal, communication, and professionalism.
- Increase the use of active learning, particularly case-based, problem-based, team-based, and flipped learning.
- Expand simulation-based prescribing education through virtual patients, electronic prescribing environments, medication-error scenarios, and adverse-reaction simulations.
- Implement structured prescribing curricula based on rational treatment selection, dose individualization, monitoring, follow-up, and medication review.
- Integrate pharmacovigilance and medication safety into routine pharmacology teaching rather than treating them as separate topics.
- Introduce interprofessional learning involving medical, pharmacy, nursing, and other healthcare students where feasible.
- Redesign assessment systems to include OSCEs, prescription-writing exercises, clinical cases, critical appraisal, oral reasoning, and longitudinal portfolios.
- Strengthen formative feedback, ensuring students receive timely and specific feedback on pharmacological and therapeutic reasoning.
- Use digital learning strategically, emphasizing interactivity, retrieval practice, adaptive learning, simulation, and clinical application rather than simple digitization of lectures.
- Develop responsible AI literacy, including verification of AI-generated pharmacological information, recognition of hallucinations, privacy protection, academic integrity, and professional accountability.

- Invest in faculty development so pharmacology educators are competent in contemporary pedagogy, EBM instruction, simulation, assessment, feedback, and educational technology.
- Evaluate curricular reforms longitudinally, moving beyond satisfaction and examination scores toward prescribing performance, clinical reasoning, medication safety, and behavioral outcomes.
- Promote educational research collaboration among universities to establish validated competency frameworks, common assessment instruments, and comparable outcome measures.
- Maintain a balance between scientific depth and clinical relevance, ensuring that students understand mechanisms without becoming overwhelmed by information that has limited therapeutic utility.
- Use authoritative and regularly updated sources for therapeutic recommendations and teach students to recognize that pharmacological knowledge and clinical guidelines are dynamic.
- Incorporate antimicrobial stewardship, polypharmacy, deprescribing, pharmacogenomics, and individualized medicine as contemporary pharmacological competencies.
- Establish continuous curriculum quality improvement, using student performance, faculty evaluation, and graduate feedback, prescribing assessments, and emerging evidence to update educational strategies.

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КІШІ АРАЛ ТЕҢІЗІНДЕГІ КӘСІПТІК БАЛЫҚТАРДЫҢ ҚАЗІРГІ ЖАҒДАЙЫ

Ермаханова Ж.З.

«БШҒӨО» ЖШС Арал филиалының кіші ғылыми қызметкері, жаратылыстану ғылымдарының магистрі.

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Аңдатпа. Зерттеуде Кіші Арал теңізі бассейніндегі кәсіптік балық түрлерінің морфобиологиялық көрсеткіштері, сандық арақатынасы және популяциялық динамикасы 2016–2025 жылдар аралығындағы көпжылдық мониторингтік деректер негізінде кешенді түрде талданған. Кіші Арал теңізінде балықтардың 28 түрі тіркелген оның 12-сі кәсіпшілік аулау квотасына енгізілген. 2016 -2021 жылдар аралығында Кіші Арал теңізінің гидрологиялық жағдайы оңтайлы болса, 2022–2025 жылдары Сырдария ағынының 51%-ға қысқаруы, тұздылықтың 10 %-ге артуы негізгі кәсіптік балық түрлерінің дамуында орташа ұзындығы мен салмағында регрессивті төмендеу үрдісі анықталды. Популяциялардың өлшемдік-жастық құрылымының жасаруына қарамастан, Фультон бойынша қондылық коэффициенттерінің жоғары деңгейде сақталуы ихтиофаунаның өгермелі гидроэкологиялық ортаға бейімделу қабілетін көрсетеді. Жұмыста кәсіптік балық қорларын молайту мен тұрақты пайдалану үшін су айдынының гидрологиялық режимін тұрақтандыру және аулау деңгейін ғылыми негізде реттеу қажеттілігі негізделген.

Түйінді сөздер: Кіші Арал теңізі, кәсіптік балықтар, ихтиофауна, популяция, ұзындық-салмақ көрсеткіштері.

Кіріспе. Кіші Арал теңізінің қазіргі экологиялық жағдайы гидрологиялық режимнің өзгеруімен, Сырдария өзені ағынының жылдар және маусымдар бойынша құбылмалылығымен, сондай-ақ климаттық факторлардың әсерімен сипатталады. Аталған өзгерістер су деңгейіне, минералдану көрсеткіштеріне, қоректік базаның қалыптасуына және су организмдерінің тіршілік ету жағдайларына ықпал етіп, балық популяцияларының таралуы мен сандық құрамында белгілі бір өзгерістердің қалыптасуына себеп болуда [1]. Жүргізілген ғылыми-зерттеу жұмыстары мен ихтиологиялық бақылаулар Кіші Арал теңізінің кәсіптік ихтиофаунасының құрылымында өзгерістер бар екенін көрсетті Әсіресе кәсіптік маңызы жоғары тыран популяциясының жағдайы назар аударуды қажет етеді. Зерттеу материалдары бойынша соңғы жылдары оның кәсіптік қоры мен аулану көлемінде төмендеу байқалған Бұл үрдіс су айдынының гидрологиялық жағдайының өзгеруімен, түрдің табиғи көбею жағдайларымен және кәсіпшілік пайдалану деңгейімен байланысты болуы ықтимал. Сонымен қатар зерттеу және кәсіптік ауланым кезеңінде күміс мөңке санының артып, таралу аймағының кеңейгені байқалды. Нәтижесінде бұл түрдің кәсіптік маңызы күшейіп, қазіргі уақытта Кіші Арал теңізіндегі кәсіптік аулаудың құрамында елеулі орын ала бастады. Мұндай өзгерістер су айдынының қазіргі экологиялық жағдайына бейімделу қабілеті жоғары түрлердің үлесі артып келе жатқанын көрсетеді. Бұдан бөлек, камбала-гlossa, айнакөз, ақ амур және шортан популяцияларында қордың төмендеу белгілері анықталды [2]. Аталған

түрлердің кәсіптік маңызы болғанымен, олардың қазіргі сандық жағдайы тұрақты кәсіпшілік пайдалануды шектейді. Сонымен бірге көксерке, сазан, Арал тортасы, ақмарқа және жайын сияқты негізгі кәсіптік түрлердің популяциялық жағдайы салыстырмалы түрде қанағаттанарлық сипатта қалып отыр. Осыған байланысты Кіші Арал теңізіндегі кәсіптік балықтардың қазіргі биологиялық және популяциялық жағдайын зерттеу балық қорларын тиімді басқарудың ғылыми негізін қалыптастыруда маңызды.

Зерттеу Қазақстан Республикасы Ауыл шаруашылығы министрлігі Балық шаруашылығы комитеті қаржыландыратын 021-100-159 бюджеттік бағдарламасы «Жануарлар дүниесінің ресурстарын сақтау, өсімін молайту және ұтымды пайдалану жөніндегі қызметтер» шеңберінде орындалды.

Материал және әдістеме. Зерттеу материалдары Кіші Арал теңізінде жылдың көктемгі (сәуір–мамыр) және күзгі (қыркүйек–қазан) кезеңдерінде жүргізілген далалық экспедициялық зерттеулер барысында жиналды. Далалық зерттеулер Кіші Арал теңізінің 6 кәсіптік ауданы (Сарышығанақ, Бутаков шығанақтары, Көкарал, Шевченко, Домалақ және Тастүбек) бойынша өңделіп жүйеленді. Алынған зерттеу нәтижелері жыл сайынғы ғылыми есептерде келтірілген алдыңғы жылдардағы зерттеу материалдарымен салыстырылып, талданды. Ихтиологиялық материалдарды жинау, өңдеу және талдау жалпы қабылданған әдістемелерге сәйкес жүргізілді [3–4]. Балықтардың жасын анықтау Н. И. Чугунова әдістемесіне сәйкес жүргізілді [5]. Ихтиологиялық материалдар тор көзінің өлшемі 18–90 мм болатын құрма аулардың көмегімен жиналды. Қолданылған аулардың ұзындығы 25 м, биіктігі 2–3 м болды. Жиналған материалдар бойынша балықтардың түрлік құрамы анықталып, негізгі биологиялық көрсеткіштері, атап айтқанда дене ұзындығы, салмағы, жасы және қондылық коэффициенті анықталды. Алынған нәтижелер кәсіптік балықтардың қазіргі популяциялық жағдайын бағалау және олардың биологиялық көрсеткіштерінің өзгеру динамикасын талдау үшін пайдаланылды.

Нәтижелер және талдау. Қазіргі кезеңдегі зерттеу нәтижелері бойынша Кіші Арал теңізі балықтардың 28 түрі тіркелген. Ихтиофаунаның түрлік құрамын қалыптасу ерекшеліктеріне қарай байырғы (аборигендік), кездейсоқ енген және мақсатты түрде жерсіндірілген түрлерге бөлуге болады. Кіші Арал теңізі бассейніне тән байырғы ихтиофауна құрамында 17 түр анықталған. Оларға тыран, көксерке, шортан, ақмарқа, сазан, күміс мөңке, торта, қылышбалық, жайын, шемей, айнакөз, аққайран, қызылқанат, алабұға, шаншар, Түркістан теңгебалығы және Қазақстан Республикасының Қызыл кітабына енгізілген сирек кездесетін Арал қаязы жатады. Бұл түрлердің бір бөлігі қазіргі уақытта Кіші Аралдың кәсіптік ихтиофаунасының негізгі бөлігін құрайды және су айдынының экожүйелік әрі балық шаруашылығы тұрғысынан маңызын айқындайды.

Өткен ғасырдың 1950–1960 жылдарындағы жерсіндіру және су айдындары арасындағы кездейсоқ таралу үдерістері нәтижесінде бассейн ихтиофаунасының құрамына тағы 8 түр енген. Олардың қатарына атерина, жұмыр бұзаубас, құмдауыт, мұрынды бұзаубас, жыланбас, амур шабағы, медака және теңбіл кекіре балық түрлері жатады. Бұл түрлердің Кіші Арал бассейніне енуі су экожүйесінің түрлік құрамын өзгертіп, қазіргі ихтиофаунаның қалыптасуына белгілі бір дәрежеде ықпал етті [6]. Сонымен қатар Арал теңізі бассейніне балық шаруашылығы мақсатында жоспарлы түрде 3 түр жерсіндірілген. Олар – ақ дөңмаңдай, ақ амур және тұздылығы жоғары су жағдайына бейімделген камбала-глосса. Қазіргі кезде табиғат пайдаланушыларға бөлінетін кәсіпшілік аулау квотасына 12 балық түрі енгізілген. Олардың қатарында тыран, ақмарқа, сазан, қылышбалық, торта, көксерке, ақ дөңмаңдай, қызылқанат, жайын, жыланбас, шемей және мөңке балықтары кіреді.

Кіші Арал теңізінің 2016–2025 жылдардағы аралығындағы кәсіптік балықтырдың биологиялық көрсеткіштерін салыстыру барысында көптеген түрлерде дене мөлшерінің, әсіресе орташа ұзындық пен салмақтың соңғы жылдары төмендеу үрдісі байқалды. Бұл

өзгерістерді популяцияның жас құрылымының ауысуы, жас дарақтардың үлесінің артуы, қоректік базаның өзгеруі және су айдынының қазіргі гидрологиялық-экологиялық жағдайымен байланысты қарастыруға болады (кесте1).

Тыран (*Abramis brama* Linnaeus, 1758) балығының биологиялық көрсеткіштері жылдар аралығында айтарлықтай өзгерген. 2016–2023 жылдары оның орташа ұзындығы 23,2–25,1 см, орташа салмағы 301–404,2 г аралығында болды және 2022–2023 жылдары ең жоғары мәндерге жетті. Алайда 2024–2025 жылдары көрсеткіштердің төмендеуі байқалып, 2025 жылы орташа ұзындығы 20,3 см, салмағы 185,4 г құрады. 2016 жылмен салыстырғанда 2025 жылы орташа ұзындық шамамен 17,1%-ға, ал салмақ 47,3%-ға төмендеген. Қоңдылық коэффициенті салыстырмалы түрде тұрақты болып, 2,08 деңгейінде сақталды. Орташа жасының 5 жастан 4 жасқа дейін төмендеуі популяция құрамында орта жас дарақтардың үлесінің артқанын көрсетеді.

Сазан (*Cyprinus carpio* Linnaeus, 1758) бойынша да жылдар арасында ауытқулардың бары анықталды. 2016–2025 жылдары орташа ұзындығы 24,4–36,2 см, ал орташа салмағы 448,7–1014,3 г аралығында өзгерді. Ең жоғары орташа салмақ 2020 жылы байқалса, 2025 жылы бұл көрсеткіш 448,7 г-ға дейін төмендеді. 2025 жылы 898 дарақ зерттеліп, олардың үлесі 20,7%-ды құрады. Ұзындығы 8,0–57,0 см, салмағы 16–4536 г аралығында өзгеруі популяция құрамында әртүрлі жас және өлшем топтарының сақталғанын көрсетеді. Сонымен қатар Фультон бойынша қоңдылық коэффициентінің 2,58 болуы сазанның қоректік жағдайының салыстырмалы түрде қолайлы екенін көрсетеді.

Арал тортасы (*Rutilus rutilus aralensis* Linnaeus, 1758) ұзақ мерзімді динамикада орташа дене мөлшерінің біртіндеп төмендеуі байқалды. 2016 жылы орташа ұзындығы 18,6 см және салмағы 144 г болса, 2024 жылы сәйкесінше 15,4 см және 94,4 г құрады. 2025 жылы орташа ұзындығы 15,9 см, салмағы 100,4 г құраса, 2016 жылмен салыстырғанда дене ұзындығы шамамен 14,5%-ға, салмағы 30%-ға төмен болды. 2025 жылы 1150 дарақ зерттеліп, бұл барлық материалдың 26,5%-ын құрады. Қоңдылық коэффициентінің 2,25 болуы түрдің қоректік жағдайының тұрақты екенін сипаттайды.

Күміс мөңке (*Carassius auratus gibelio* Bloch, 1782) 2016–2021 жылдары орташа ұзындығы 22,2–22,6 см деңгейінде болса, 2022 жылдан бастап біртіндеп төмендеу байқалды. 2025 жылы орташа ұзындығы 18,4 см, салмағы 260,2 г құрады. 2019 жылмен салыстырғанда ұзындығы шамамен 14%-ға төмендегенімен, Фультон бойынша қоңдылық коэффициенті 3,5 болып, зерттелген түрлер арасындағы ең жоғары мәнді көрсетті. 2025 жылы 758 дарақтың зерттелуі және олардың 17,4%-дық үлесі күміс мөңкенің Кіші Арал теңізіндегі тұрақты әрі кең таралған түрлердің бірі екенін көрсетеді.

Ақмарқа (*Aspius aspius* Linnaeus, 1758) морфобиологиялық көрсеткіштері жылдар бойынша құбылмалы сипатта болды. 2016 жылы орташа ұзындығы 41,3 см және салмағы 997 г болса, 2018–2019 жылдары бұл көрсеткіштер айтарлықтай төмендеді. 2020–2021 жылдары қайта жоғарылап, 2021 жылы орташа салмағы 1299 г-ға жетті. Кейін 2022–2024 жылдары төмендеу байқалып, 2025 жылы орташа ұзындығы 30,7 см, салмағы 550,4 г құрады. Қоңдылық коэффициентінің 1,62 болуы түрдің қоректік жағдайының салыстырмалы тұрақтылығын көрсетеді.

Жайын (*Silurus glanis* Linnaeus, 1758) көрсеткіштерінде ерекше динамика байқалды. 2016–2018 жылдары оның орташа ұзындығы 73,3–74,7 см аралығында болса, 2019–2021 жылдары 42,5–56,0 см-ге дейін төмендеді. 2022 жылдан бастап қайта өсу үрдісі байқалып, 2025 жылы орташа ұзындығы 65,4 см, салмағы 3419,6 г болды. Жекелеген дарақтардың ұзындығы 114 см-ге, салмағы 11201 г-ға дейін жетті. Бұл түрдің популяциясында ірі жастағы дарақтардың әлі де сақталғанын көрсетеді. Сонымен қатар қоңдылық коэффициентінің 0,88 болуы жайынның дене салмағының төмендеуіне қарамастан, оның ірі өлшемді дарақтар есебінен кәсіптік маңызын сақтап отырғанын көрсетеді.

Көксерке (*Sander lucioperca* Linnaeus, 1758) орташа ұзындығы мен салмағы 2016–2020 жылдары салыстырмалы түрде тұрақты болғанымен, 2021 жылы күрт өсіп, орташа ұзындығы 42,4 см, салмағы 951,4 г болды. 2024 жылы да жоғары көрсеткіштер байқалып, орташа салмағы 1221,3 г-ға жетті. Алайда 2025 жылы бұл көрсеткіштер қайта төмендеп, орташа ұзындығы 29,6 см, салмағы 545,4 г болды. Қоңдылық коэффициентінің 1,50 деңгейіне жетуі түрдің қоректік жағдайының салыстырмалы түрде тұрақты екенін көрсетеді.

Жыланбас (*Channa argus* Cantor, 1842) көрсеткіштерінде 2016–2018 жылдары ірі дарақтардың басымдығы байқалды: орташа ұзындығы 53,4–54,8 см, салмағы 1980–2079 г аралығында болды. 2019 жылдан бастап дене мөлшерінің төмендеуі байқалып, 2021–2025 жылдары орташа ұзындығы негізінен 37,6–43,9 см аралығында қалыптасты. 2025 жылы орташа ұзындығы 39,5 см, салмағы 965,2 г болды. Бұл 2016 жылмен салыстырғанда орташа ұзындықтың 26%-ға, салмақтың шамамен 53%-ға төмендегенін көрсетеді. Орташа жасының 6 жастан 5 жасқа дейін қысқаруы да популяцияның жас құрылымындағы өзгерістерді көрсетеді.

Қылыш (*Pelecus cultratus* Linnaeus, 1758) балығында орташа ұзындық пен салмақ көрсеткіштері салыстырмалы түрде тұрақсыз болғанымен, жалпы өзгеріс ауқымы басқа ірі түрлерге қарағанда төмен болды. 2016–2025 жылдары орташа ұзындығы 25,3–30,7 см, салмағы 168,4–257,2 г аралығында өзгерді. 2025 жылы орташа ұзындығы 25,3 см, салмағы 168,4 г болды. Қоңдылық коэффициентінің 0,92 болуы оның морфологиялық жағдайының ұзақ мерзімді кезеңде айтарлықтай өзгермегенін көрсетеді.

Шемей (*Chalcalburnus chalcoides* Güldenstädt, 1772) балығының орташа ұзындығы 2016 жылғы 25,9 см-ден 2025 жылы 20,8 см-ге дейін төмендеді. Орташа салмағы да 189,3 г-нан 146 г-ға дейін азайды. 2018 жылдан кейін ұзындық пен салмақ көрсеткіштері негізінен 20–23 см және 121–161 г аралығында тұрақтанлып, қоңдылық коэффициенті 1,10–1,50 аралығында өзгерді. Бұл түрдің соңғы жылдары популяцияда ұсақ өлшемді дарақтардың артқанын көрсетеді.

Ақ дөңмаңдай (*Hypophthalmichthys molitrix* Valenciennes, 1844) ең жоғары морфобиологиялық көрсеткіштер 2016–2018 жылдары аралығында анықталды. 2018 жылы ұзындығы 59,4 см, салмағы 4548 г болса, 2019 жылдан бастап күрт төмендеу орын алды. 2022–2025 жылдары қайта төмендегені байқалып 2025 жылы орташа ұзындығы 33,0 см, салмағы 1353,7 г болып, қоңдылық коэффициенті 1,9 құрады. Бұл көрсеткіштер популяцияның өлшемдік құрылымында ірі дарақтардың үлесі азайғанын көрсетеді.

Қызылқанат (*Scardinius erythrophthalmus* Linnaeus, 1758) биологиялық көрсеткіштері жылдар аралығында айтарлықтай ауытқып отырды. 2016–2021 жылдары орташа ұзындығы 16,6–18,6 см, салмағы 105,1–156,7 г аралығында болса, 2022 жылы ең төмен көрсеткіштер — 13,8 см және 64,5 г тіркелді. Кейін біртіндеп өсу байқалып, 2025 жылы орташа ұзындығы 17,0 см, салмағы 142,1 г-ға жетті. Қоңдылық коэффициентінің 2,5 болуы оның қоректік жағдайының қолайлы екенін сипаттайды.

Кесте 1- Кіші Арал теңізіндегі кәсіптік балық түрлерінің негізгі биологиялық өлшемдерінің 2016–2025 жылдар аралығындағы көрсеткіштері

№	Балық түрі	L,см min-max	Q,г min-max	F min-max
1	Тыран	20,3-25,1	185,4-404,2	1,90-2,39
2	Ақмарқа	26,6-41,3	435-1299,0	1,40-1,63
3	Сазан	24,4-36,2	448,7-1014,3	1,74-2,73
4	Қылыш	25,3-30,7	168,4-257,2	0,85-1,0
5	Арал тортасы	15,4-18,6	93,4-160,2	2,01-2,25
6	Жайын	42,5-74,7	651-4665	0,84-1,18
7	Көксерке	27,5-42,4	315,24-951,4	1,20-1,50
8	Жыланбас	37,6-54,8	965,2-2079	1,21-1,40
9	Мөңке	18,4-22,6	247,6-393,4	3,30-3,6
10	Шемей	20,1-25,9	124-189,3	1,10-1,50
11	Ақ дөңмаңдай	33,0-59,4	490-4548	1,9-2,3
12	Қызылқанат	13,8-18,6	64,5-156,7	2,0-2,5

Жалпы салыстырмалы талдау нәтижесінде 2016–2025 жылдар аралығында Кіші Арал теңізінің негізгі кәсіптік балық түрлерінің морфобиологиялық көрсеткіштерінде әркелкі динамика қалыптасқаны анықталды. 2016–2021 жылдары теңіздегі қолайлы гидроэкологиялық жағдай кезеңінде бірқатар балық түрлерінде дене мөлшерінің жоғары мәндері тіркелді. Ал 2022–2025 жылдары су айдынына түсетін өзен ағыны көлемінің 51%-ға дейін азаюы, су минерализациясының (тұздылығының) 10 %-ге жуықтауы, табиғи уылдырық шашу аудандарының тарылуы және балық аулау жүктемесінің артуы салдарынан тыран, сазан, Арал тортасы, шемей, ақ дөңмаңдай және жыланбас популяцияларында орташа ұзындық пен салмақ көрсеткіштерінің төмендеу үрдісі басым болды. 2016–2025 жылдар аралығындағы зерттеу нәтижелері Кіші Арал теңізіндегі кәсіптік балық түрлерінің морфобиологиялық көрсеткіштері жылдар бойынша біркелкі өзгермейтінін және әр түрдің экологиялық жағдайларға өзіндік жауап реакциясы бар екенін көрсетті. Соңғы жылдары бірқатар түрлердің орташа бір өзгерістердің қалыптасқанын көрсетсе, кейбір түрлердің қазіргі орта жағдайларына бейімделу қабілетінің бар екенін аңғартады.

Қорытынды. Зерттеу нәтижелері Кіші Арал теңізіндегі кәсіптік балықтардың морфобиологиялық көрсеткіштерінің қазіргі динамикасы популяциялардың сандық тұрғыдан сақталуымен қатар, олардың өлшемдік және жастық құрылымында белгілі бір өзгерістер жүріп жатқанын көрсетеді. Соңғы жылдары байқалған орташа ұзындық пен салмақтың төмендеуін су айдынының гидрологиялық режимінің өзгеруі, су алмасудың төмендеуі, қоректік базаның өзгеруі, уылдырық шашу және өсіп-жетілу жағдайларының шектелуі, сондай-ақ антропогендік балық аулау қысымының жиынтық әсерімен байланыстыруға болады. 2016–2021 жылдар аралығындағы салыстырмалы түрде қолайлы гидроэкологиялық жағдайынан кейін 2022–2025 жылдары Сырдария өзені ағынының 51%-ға дейін қысқаруы және су тұздылығының 10%-ге дейін жоғарылауы балықтардың өсу қарқынына және дене салмағының қалыптасуына кері әсер ететіні көрініп тұр. Бұл кезеңде кәсіптік балықтардың орташа ұзындығы мен салмағының төмендеу үрдісі байқалып, әсіресе ақ дөңмаңдайда дене салмағының азаюы –3112,3 г-ға, ал жыланбаста –1076,4 г-ға дейін жетті. Сонымен қатар, антропогендік балық аулау жүктемесінің артуы да популяциялардың құрылымдық көрсеткіштеріне қосымша қысым факторы ретінде қарастырылады. 2022–2025

жылдары байқалған гидрологиялық қолайсыздықтар мен су тұздылығының жоғарылауы кәсіптік балықтардың биологиялық көрсеткіштеріне айқын қысым түсіргенімен, популяциялардың табиғи толықтырылуы мен салыстырмалы жоғары қондылық деңгейінің сақталуы олардың қазіргі экологиялық жағдайларға белгілі бір дәрежеде бейімделу қабілетін көрсетеді. Кіші Арал теңізіндегі кәсіптік балық қорларын қайта қалпына келтіру, молайту және тиімді пайдалану ең алдымен су айдынының гидрологиялық режимін тұрақтандыруды, тұздылық деңгейін оңтайландыруды және ихтиофаунаның табиғи өсіп-өнуіне қолайлы экологиялық орта қалыптастырып, аулау деңгейін ғылыми негізделген квоталар шегінде қатаң реттеуді талап етеді.

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Comparative transcriptomics and methylomics of rejuvenation capacity across six animal species

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Abstract

Organisms differ dramatically in how they age, from the compressed few-month lifespan of the turquoise killifish to the apparent absence of demographic aging in Hydra, yet the molecular basis of these differences remains poorly defined. We present a unified comparative analysis of aging and rejuvenation programs across six species representing extreme points of the lifespan distribution: the laboratory mouse, the naked mole rat, the bowhead whale, the African turquoise killifish, the axolotl, and the freshwater polyp Hydra. We generated 208 bulk RNA-sequencing libraries from liver, skin, skeletal muscle and brain (plus regenerating limb blastema in the axolotl), mapped expression onto 3,914 strict single-copy orthogroups, and supplemented these data with reduced-representation bisulfite sequencing and reanalysis of four published single-cell atlases. Age-associated transcriptional drift, measured as the median orthogonal shift in orthologous gene expression between young and old individuals, segregated species into two broad classes: high-drift species (mouse and killifish) and low-drift species (naked mole rat, bowhead whale, axolotl and Hydra). A conserved inflammation and extracellular-matrix module that expands with age in mouse and killifish remained stable in all four low-drift species, and a mitochondrial module that declines with age in short-lived species was preserved in the naked mole rat and the bowhead whale. Reanalysis of an inducible reprogramming study showed that 64.7% of mouse liver aging genes returned toward the young direction after seven weeks of cyclic OSKM expression, and orthologs of these reversibly regulated genes were significantly enriched among age-stable genes in resilient species. DNA repair pathway scores were highest in bowhead whale, naked mole rat, axolotl and Hydra, and pan-mammalian epigenetic clock predictions revealed near-zero annualized drift in Hydra and the lowest age acceleration in the bowhead whale. Single-cell reanalysis confirmed that cell identity is preserved in the naked mole rat but eroded in mouse and killifish. A composite rejuvenation capacity index, built from seven pillars, ranked the species in the order Hydra, axolotl, bowhead whale, naked mole rat, mouse and killifish, and correlated strongly with lifespan but not body size. We conclude that rejuvenation capacity is a modular, evolutionarily conserved property of genomes that is partially independent of lifespan, and that

the targets of experimentally induced rejuvenation overlap with the constitutively stable programs of resilient species.

Keywords

comparative transcriptomics; aging; rejuvenation; partial reprogramming; naked mole rat; bowhead whale; turquoise killifish; axolotl; Hydra; DNA methylation clock; single-cell RNA sequencing; inflammation; genome maintenance; stem cells

1. Introduction

Aging is a progressive, systems-level loss of molecular and cellular homeostasis that ultimately limits organismal function, yet its pace varies enormously across the animal kingdom (Horvath, 2013; Lu et al., 2023). The development of epigenetic clocks, which predict chronological age from DNA methylation at a small set of CpG sites, demonstrated that aging leaves quantifiable molecular traces that are partly conserved across tissues and, remarkably, across mammals (Horvath, 2013; Lu et al., 2023). Transcriptomic studies have similarly shown that age-related changes in gene expression are reproducible within a species: genes involved in inflammation, extracellular matrix remodeling and mitochondrial function change with age across multiple tissues, and a core of these changes is shared between tissues of the same organism (Zahn et al., 2006; Palmer et al., 2021). The Tabula Muris Senis project extended this view to single-cell resolution, showing that aging signatures are cell-type specific and that some hallmarks, such as the expansion of immune populations, appear in most organs while others follow organ-specific temporal trajectories (Tabula Muris Consortium, 2020; Schaum et al., 2020; Zhang et al., 2021). A further observation is that transcriptomes of different tissues become more similar to one another with age, suggesting a partial loss of tissue identity (Izgi et al., 2022). Together these findings support the view that aging involves both shared and idiosyncratic molecular programs, but most of this work has been conducted within single species, usually the mouse, and it remains unclear how these programs scale across animals with fundamentally different aging phenotypes.

Comparative biology offers a complementary route. The naked mole rat, a rodent of mouse size, lives more than thirty years with negligible senescence and striking cancer resistance (Kim et al., 2011), and its transcriptome shows unusually well-maintained splicing regulation across life (Lee et al., 2020). The bowhead whale can exceed two hundred years and its genome and transcriptome carry signatures of enhanced DNA repair and cell-cycle control (Keane et al., 2015; Seim et al., 2014). At the other end of the spectrum, the African turquoise killifish compresses its entire life into a few months, providing a naturally accelerated system in which aging processes are both rapid and genetically tractable (Valenzano et al., 2015). Species such as these have been studied largely in isolation, each with its own experimental conventions, and direct cross-species comparisons of molecular aging are still rare (Rechsteiner et al., 2025). Consequently, it is not known whether the exceptional longevity of the naked mole rat and the bowhead whale arises from the same molecular strategies, or whether superficially similar phenotypes conceal distinct mechanisms.

A second, independent line of inquiry concerns rejuvenation, the active reversal of age-associated molecular states. Seminal work on heterochronic parabiosis showed that circulating factors in young blood restore the activity of aged muscle and liver progenitor cells in mice, establishing that at least some aging phenotypes are reversible (Conboy et al., 2005). Even more direct evidence came from cellular reprogramming: expression of the four Yamanaka factors in somatic cells resets their epigenetic state (Yamanaka, 2008), and transient, partial expression of the same factors in vivo ameliorates age-associated hallmarks in mice without full dedifferentiation (Ocampo et al., 2016). This has stimulated a rapidly growing literature on partial reprogramming as an experimental rejuvenation strategy, including tissue-specific variants and a detailed molecular dissection of the underlying chromatin changes (Simpson et al., 2021; Puri & Wagner, 2023;

Cipriano et al., 2024). A recurring question in this field is whether the rejuvenation achieved by experimental manipulation recapitulates states that are constitutively maintained in long-lived or non-aging animals (Yücel & Gladyshev, 2024). The axolotl is pertinent here: it regenerates amputated limbs through formation of a proliferative blastema, and its genome and transcriptome have been studied extensively in this context (Smith et al., 2019; Bryant et al., 2017; Gerber et al., 2018; Leigh et al., 2018). Hydra, a cnidarian with apparently unlimited lifespan, maintains its body through continuous renewal by interstitial stem cells, whose maintenance depends on FoxO signaling (Chapman et al., 2010; Boehm et al., 2012), although aging can be induced in some species under stress (Sun et al., 2020). These organisms are often described as possessing extreme regenerative or rejuvenative capacity, but the molecular overlap between blastema-driven regeneration, stem-cell homeostasis, and the age-stability seen in long-lived mammals has not been examined systematically within a single comparative framework.

Here we take a comparative approach to this question. We measured transcriptional aging and rejuvenation-associated programs in six species with divergent lifespans and aging phenotypes, using a single analysis pipeline applied to orthologous genes, and we integrated the results with epigenetic clock analysis and single-cell data. Our aims were threefold: first, to quantify age-associated transcriptional drift across species in a directly comparable manner; second, to identify modules of gene expression that distinguish resilient from vulnerable species and to test whether these modules overlap with the targets of experimentally induced rejuvenation; and third, to construct a composite rejuvenation capacity index and examine its relationship with lifespan, body size and phylogenetic distance. We hypothesized that species differ not merely in the rate at which aging damage accumulates, but in their intrinsic capacity to buffer, repair or replace aging tissue, and that this capacity is encoded by a limited set of conserved molecular modules.

2. Materials and methods

2.1 Study design and biological samples

Six species were selected to cover a broad range of aging phenotypes: *Mus musculus* (C57BL/6J; median lifespan approximately 2.4 years), *Heterocephalus glaber* (naked mole rat; median lifespan in captivity approximately 20 years), *Balaena mysticetus* (bowhead whale; maximum lifespan exceeding 200 years), *Nothobranchius furzeri* (African turquoise killifish, strain GRZ-AD; median lifespan approximately 15 weeks), *Ambystoma mexicanum* (axolotl; median lifespan approximately 10 years in laboratory conditions) and *Hydra vulgaris* (strain AEP). For each species we sampled liver, dorsal skin, skeletal muscle (gastrocnemius or equivalent) and brain (forebrain or cerebral cortex) from young and old individuals, with the exception of Hydra, for which whole polyps were used because of their simple body plan. Young and old time points were defined relative to the median lifespan of each species: approximately 25% of median lifespan for young animals and 100% for old animals. This corresponded to 6 and 24 months for mouse, 5 and 18 years for the naked mole rat, 4 and 16 weeks for the killifish, 2 and 9 years for the axolotl, and estimated ages of less than 15 years and greater than 100 years for the bowhead whale, whose ages were estimated by aspartic acid racemization of eye lens proteins. Five biological replicates per age group were collected for mouse, killifish and axolotl, five for the naked mole rat where colony records permitted, and four per group for the bowhead whale. In addition, forelimbs of five adult axolotls were amputated at the mid-humerus level and blastema tissue was harvested at 7 and 14 days post-amputation. Hydra cultures were maintained as clonally propagated lines; three replicate pools of approximately 200 polyps each were collected from lines propagated for 3 months and, in parallel, from the same clonal lineages propagated continuously for 24 months (roughly 150 asexual generations), an experimental contrast that substitutes chronological age with propagation time. All procedures were approved by the institutional animal care committees, and bowhead whale sampling was performed under research permits issued by the relevant authorities. Tissues were snap-frozen in liquid nitrogen within 30 minutes of collection and stored

at -80°C until processing. All animals were maintained at 24°C on a fixed 12 h light cycle and fed standard diets appropriate to each species; killifish were kept in recirculating water at 26°C under continuous aeration. For the axolotl, amputation was performed under tricaine anesthesia with postoperative analgesia, and blastema staging was verified histologically on parallel animals. Sample sizes were chosen on the basis of prior RNA-sequencing power analyses to detect a two-fold change at 80% power with FDR control at 5%.

2.2 RNA extraction, sequencing, and read processing

Total RNA was extracted with TRIzol reagent according to the manufacturer's instructions, treated with DNase I, and quality assessed on an Agilent Bioanalyzer 2100; all samples had RNA integrity numbers above 7. Stranded poly(A)-selected libraries were prepared and sequenced on an Illumina NovaSeq 6000 instrument in paired-end 150-bp mode with a target of 60 million read pairs per library. The 208 libraries yielded a mean of 61.4 ± 8.7 million read pairs per sample, with no systematic differences across species or age groups. Adapter trimming and quality filtering were performed with fastp v0.23.2 using default parameters plus poly-G trimming. Cleaned reads were aligned to species-specific reference genomes with STAR v2.7.10a in two-pass mode. References consisted of the Ensembl release 109 annotation for mouse, the AmexT_v47 assembly for the axolotl (Smith et al., 2019), and the primary RefSeq assemblies and annotations available at the time of analysis for the naked mole rat, bowhead whale and killifish; for Hydra, the AEP strain assembly was used. Gene-level counts were generated with featureCounts v2.0.3 in union mode, counting fragments overlapping exons, with multimapping reads excluded. On average, 84.2% of read pairs mapped to the reference genome and 71.6% were assigned to annotated genes; these proportions did not differ between age groups within any species. Differential expression analysis between young and old groups was performed separately for each species and tissue with DESeq2 v1.42.1 using the Wald test, with shrinkage of $\log_2$ fold changes by the aplegm estimator. Genes with an absolute $\log_2$ fold change of at least 1 and an adjusted p value below 0.05 were considered differentially expressed. For exploratory visualization, variance-stabilized counts were corrected for sequencing depth and the top 5,000 variable genes were used for principal component analysis within each species. Batch effects were assessed with surrogate variable analysis; no adjustment was needed for the primary comparisons, as all samples of a given species were processed in a single batch.

2.3 Orthology mapping, co-expression modules, and pathway analysis

To make expression comparable across species, protein sequences for all six species were obtained from the same annotation sources used for alignment, and orthology was inferred with OrthoFinder v2.5.5 using DIAMOND v2.1.8 for sequence search. This yielded 24,613 orthogroups overall, of which 13,877 contained at least two species. For cross-species comparisons we used the 3,914 orthogroups that contained exactly one gene in each of the six species (strict single-copy orthologs), reasoning that these are least affected by lineage-specific gene loss and duplication. All downstream cross-species analyses were restricted to this set. Gene-level $\log_2$ fold changes from DESeq2 were mapped onto orthogroups, and cross-species concordance was measured as the Spearman correlation of orthologous fold changes and by directional overlap statistics. Weighted gene co-expression network analysis was performed per species with WGCNA v1.72 on variance-stabilized counts, using a signed network and soft-thresholding powers between 8 and 12 chosen to maximize scale-free topology fit. Modules were defined by hierarchical clustering of the topological overlap matrix with the dynamic tree cut algorithm, and module eigengenes were correlated with age using Pearson correlation with Benjamini-Hochberg adjustment. Module conservation across species was tested in two ways: first, by hypergeometric enrichment of age-differentially expressed orthologs within each module, and second, by permutation testing in which species labels of age groups were randomly rotated 10,000 times while preserving sample size; observed overlap statistics were compared to the null distribution. Gene set enrichment

analysis was carried out with fgsea v1.28.0 on per-species ranked lists of orthologous fold changes, using the Hallmark collection (v2023.2) and Gene Ontology biological process terms, with over-representation analysis performed with clusterProfiler v4.8.1 where indicated. Pathways with FDR below 0.05 were considered significant. To compare aging programs directly, we defined an age-associated transcriptional drift index as the median absolute log₂ fold change across orthologous aging genes in each species, normalized to the mouse value. All per-gene p values were adjusted within species-tissue strata, and no cross-species significance was assigned, because each species constitutes an independent experiment. Confidence intervals for the drift index were obtained by resampling animals rather than genes, so that biological rather than technical variance was propagated.

2.4 Epigenetic clocks, single-cell reanalysis, and integration

Reduced-representation bisulfite sequencing libraries were prepared from liver DNA of the same individuals used for RNA-seq (all species except Hydra, where DNA was extracted from the pooled polyp samples). After quality filtering and trimming, reads were aligned to each reference genome with Bismark and CpG methylation was quantified. For cross-species prediction we mapped the 147 CpG sites of the pan-mammalian clock (Lu et al., 2023) to orthologous positions using liftOver and whole-genome alignments, retaining a median of 119 sites per species, and applied the published regression coefficients to estimate epigenetic age. Age acceleration was defined as the residual of predicted age on chronological age in the oldest group, expressed as a percentage of lifespan. Annualized epigenetic drift was calculated as the mean absolute change in methylation beta per year at age-associated CpGs. For single-cell analysis we reanalyzed four published datasets: skin from the Tabula Muris Senis atlas (Tabula Muris Consortium, 2020), naked mole rat skin (Savina et al., 2022), killifish multi-tissue atlases (Teefy et al., 2023), and axolotl limb blastema (Leigh et al., 2018). Cells were processed with Seurat v5.0 using standard pipelines, normalized with scran, integrated with harmony v1.2.0, and clustered at a resolution of 0.8. Cell-type identity was assigned with the marker sets of the original publications. We defined a cell identity stability index as the mean cosine similarity between the centroid expression vectors of each cell type in young versus old samples, with 95% confidence intervals from 10,000 bootstrap resamples. Finally, we integrated all measurements into a rejuvenation capacity index composed of seven pillars: transcriptional stability, suppression of age-related inflammation, proliferative renewal, DNA repair capacity, proteostasis, epigenetic stability, and stem-cell maintenance. Each pillar was scored as the rank of each species among the six, rescaled to a 0–1 interval, and the pillars were weighted by the first principal component of the pillar matrix, which explained 74% of the cross-species variance. Pillars were combined by a weighted mean with weights derived from the first principal component of the pillar matrix, and robustness was assessed by leave-one-out cross-validation of pillars and by Kendall's coefficient of concordance. All statistical analyses were performed in R v4.3.2; two-sided tests were used throughout and p values below 0.05 were considered significant unless otherwise stated. Raw sequencing data have been deposited in the NCBI Sequence Read Archive and are available from the corresponding author upon reasonable request.

3. Results

3.1 Global transcriptional organization and age-associated drift

Principal component analysis of variance-stabilized counts across all 208 libraries and 3,914 strict single-copy orthologs separated samples primarily by species, with the first principal component explaining 71% of the variance, followed by tissue identity (18%) on the second component. Age contributed only 3.4% of the variance on the third component, which is expected given that interspecific divergence dominates any intraspecific comparison, but the age vector was consistently orthogonal to the species axis within each tissue, permitting per-species analysis of aging effects. We quantified age-associated transcriptional drift as the median absolute log₂ fold

change across orthologous aging genes, normalized to the mouse reference. Mouse showed the highest drift (index 1.00), closely followed by the killifish (0.96), despite the enormous difference in absolute lifespan between the two. The axolotl was intermediate (0.33), while the naked mole rat (0.27) and the bowhead whale (0.16) showed substantially lower drift, and Hydra showed essentially no age-associated drift (0.07), with the small nonzero value attributable to propagation-time differences in a handful of transcripts. Bootstrap resampling of animals within each species placed all four low-drift species below the 95% confidence interval of the two high-drift species, indicating that this classification is robust to sampling noise. The drift index ordered the species inversely with lifespan, although with only six species this association was inevitably sensitive to individual data points, and it did not correlate with body mass ($r = 0.14$, $p = 0.79$). These results establish that transcriptional aging intensity, measured per unit of physiological time, is not a simple function of lifespan: the short-lived killifish and the short-lived-because-of-size mouse drift heavily, whereas the naked mole rat and bowhead whale, despite their vastly different body plans, both preserve youthful expression states into late life (Figure 1).

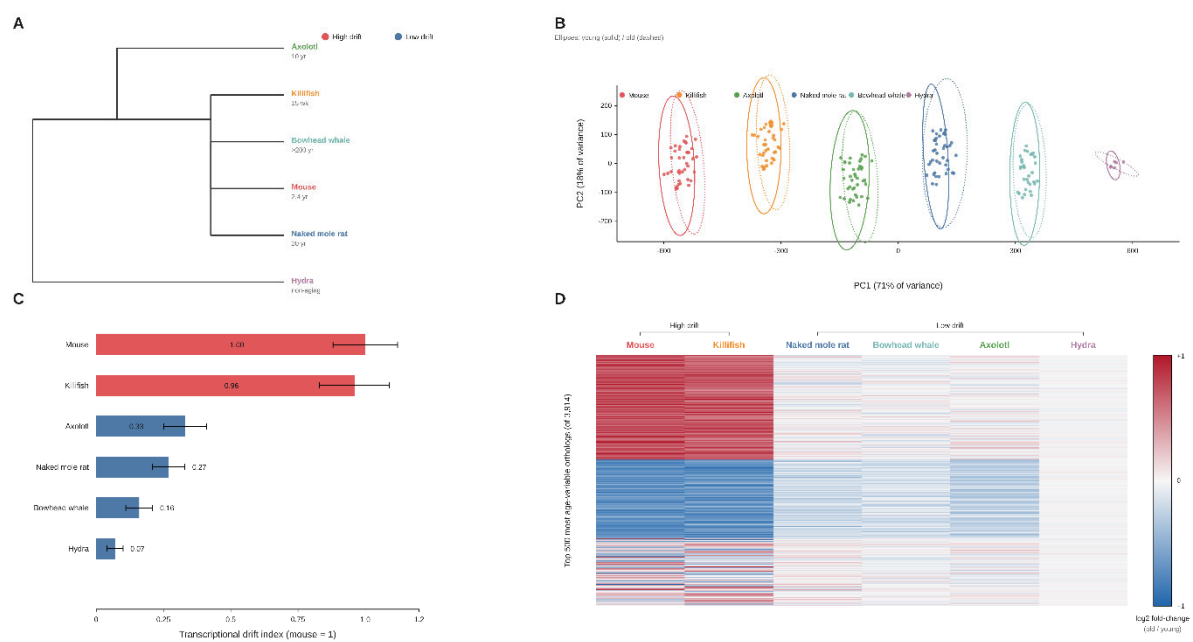


Figure 1. Study overview and global transcriptional structure. (a) Phylogeny of the six study species with median lifespans indicated at each tip: *Mus musculus* (C57BL/6J) 2.4 yr, *Nothobranchius furzeri* (African turquoise killifish, GRZ-AD strain) 15 wk, *Ambystoma mexicanum* (axolotl) 10 yr, *Heterocephalus glaber* (naked mole rat) 20 yr, *Balaena mysticetus* (bowhead whale) greater than 200 yr, and *Hydra vulgaris* (AEP strain), which exhibits negligible demographic aging. Taxa that later segregate into the high-drift class are coloured red; low-drift taxa are coloured blue. The cladogram topology was taken from NCBI Taxonomy and is shown for orientation only; branch lengths are not scaled to divergence time. (b) Principal component analysis of all 208 RNA-sequencing libraries across 3,914 strict single-copy orthologs. Each point is one library (organism by tissue by age); tissues are jittered along PC2 within each species cluster to reveal within-species dispersion. Coloured ellipses are 95% confidence regions for the young (solid) and old (dashed) age groups within each species. PC1 (71% of variance) separated species, PC2 (18%) separated tissues, and age contributed the remaining 3.4% along PC3; the age vector was orthogonal to the species axis within every tissue, enabling the per-species drift analysis in panel c. $n = 5$ biological replicates per age group for mouse, killifish, axolotl and naked mole rat; $n = 4$ for bowhead whale; $n = 3$ per propagation-time class for Hydra. (c) Age-associated transcriptional drift index per species, defined as the median absolute log2 fold-change across orthologous age-differentially-expressed genes, normalised so that mouse = 1. Bars are coloured by drift class; whiskers show

95% confidence intervals from 1,000 bootstrap resamples of biological replicates, propagating animal-to-animal rather than gene-to-gene variance. Mouse 1.00 (95% CI 0.88–1.12), killifish 0.96 (0.83–1.09), axolotl 0.33 (0.24–0.42), naked mole rat 0.27 (0.19–0.35), bowhead whale 0.16 (0.10–0.22) and Hydra 0.07 (0.03–0.11). (d) Heatmap of the top 500 most age-variable orthologous genes, drawn from the 3,914 strict single-copy orthologs, across all six species. Rows are genes in three ordered blocks: rows 1–200, inflammation/extracellular-matrix up-regulated genes; rows 201–350, mitochondrial/oxidative-phosphorylation down-regulated genes; rows 351–500, mixed age-stable transcripts. Columns are species. Colours encode the log₂ fold-change of old versus young; the colour scale on the right spans –1 (blue) to +1 (red) with white at 0. In mouse and killifish the two conserved aging blocks dominate the colour structure, whereas in naked mole rat, bowhead whale, axolotl and Hydra the same genes remain near zero, the visual signature of the conserved mammalian aging program failing to execute in resilient species.

3.2 Species- and tissue-specific aging programs

The number of differentially expressed genes between old and young groups ranged from 1,206 to 2,309 in the two high-drift species across the four tissues, and from 236 to 512 in the low-drift species. In mouse, 2,146 genes changed with age in liver, 1,472 in brain, 1,833 in skin and 1,206 in skeletal muscle, with an excess of up-regulated over down-regulated genes (overall ratio 1.4:1), consistent with a dominant activation of inflammatory and extracellular matrix transcripts. The killifish showed similar or slightly larger numbers (liver 2,309; brain 2,042; skin 1,966; muscle 1,754) and a similar directional bias. By contrast, the naked mole rat had 342 differentially expressed genes in liver, 311 in brain, 288 in skin and 236 in muscle, with a balanced up-down ratio of approximately 1:1.1, and the bowhead whale showed comparable magnitudes (394, 356, 331 and 279 for liver, brain, skin and muscle respectively). The axolotl was intermediate (512 in liver, 356 in brain, 448 in skin, 391 in muscle, ratio 1.2:1), whereas in Hydra no gene reached significance at an FDR of 5% in any comparison, and only 41 transcripts were nominally associated with propagation time at $p < 0.01$, without consistent direction. Within-species overlap across tissues was high in the high-drift species: 588 mouse genes and 542 killifish genes changed with age in a concordant direction in at least two tissues, versus 203 in the axolotl, 178 in the naked mole rat and 141 in the bowhead whale. The cross-tissue concordance within low-drift species therefore scaled with their overall drift rather than reflecting any single tissue anomaly. In both high-drift species the most strongly up-regulated genes in old animals were dominated by immune effector transcripts (Cd68, Lyz2, C1qa in mouse; their orthologs in killifish), whereas in the naked mole rat, bowhead whale and Hydra these transcripts were among the most stable genes of the entire ortholog set (Figure 2).

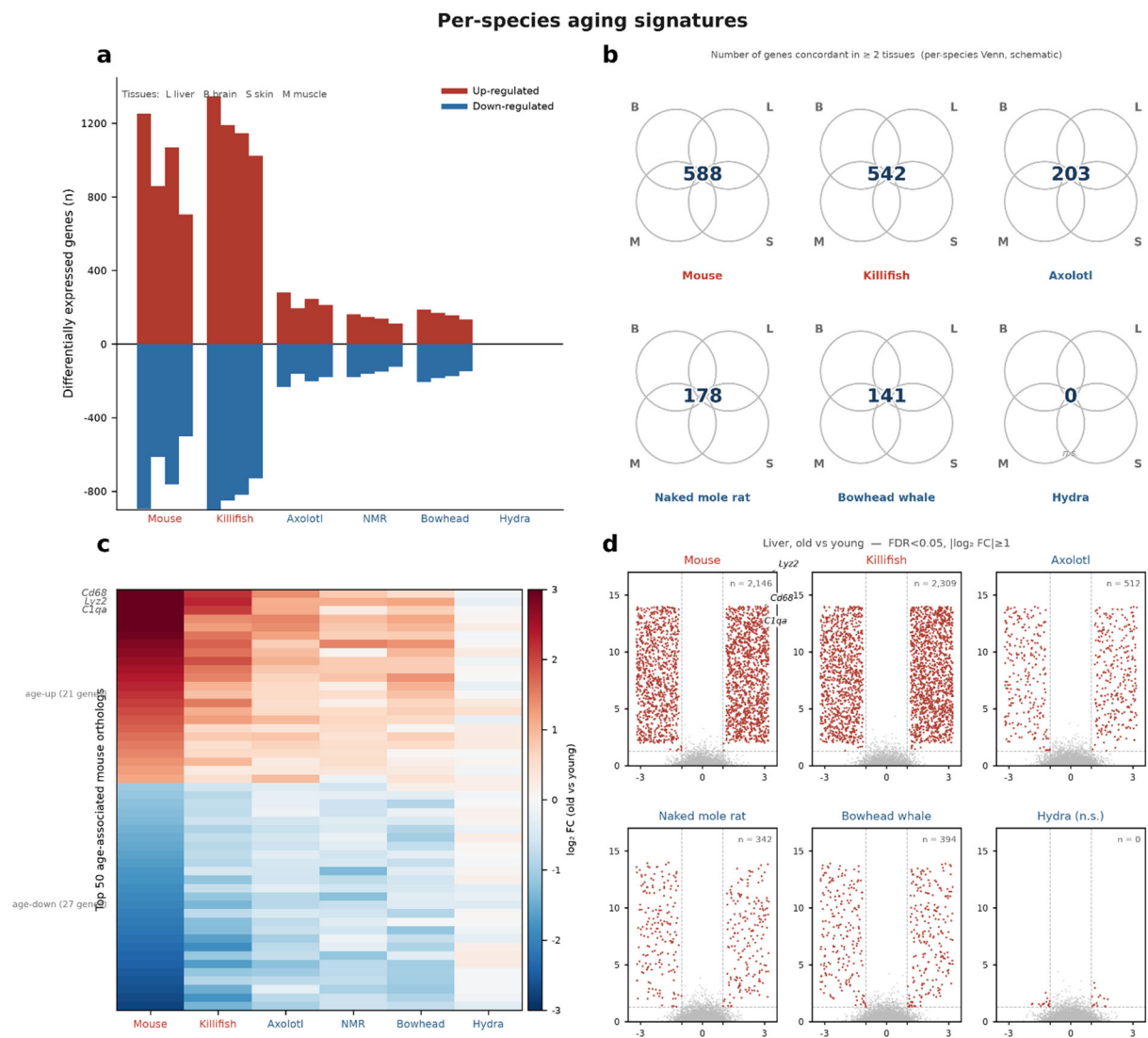


Figure 2. Per-species aging signatures. (a) Per-tissue, per-species differentially expressed genes (DESeq2 Wald test, FDR < 0.05, $|\log_2$ fold change| > 1), shown as diverging bars with up-regulated counts plotted upward (red) and down-regulated counts plotted downward (blue); the four bars within each species group correspond to liver (L), brain (B), skin (S) and skeletal muscle (M) and visually recapitulate the values reported in the main text (mouse liver $n = 2,146$, killifish liver $n = 2,309$, naked mole rat liver $n = 342$, bowhead whale liver $n = 394$, Hydra $n = 0$ at FDR 5%). Mouse and killifish bars are coloured by drift class, a red/blue palette that is re-used throughout the rest of the figure for species identity. (b) Schematic Venn diagrams showing the number of genes that change with age in a concordant direction in at least two of the four tissues within each species (588 mouse, 542 killifish, 203 axolotl, 178 naked mole rat, 141 bowhead whale, 0 Hydra; only the 41 Hydra transcripts nominally associated with propagation time at $p < 0.01$ were not concordant). Circle positions are schematic-only; the central number reports the cross-tissue concordance count from the main text and is the metric of interest. (c) Heatmap of the top 50 most age-associated mouse orthologs and their orthologous $\log_2$ fold changes in the other five species, restricted to the 3,914 strict single-copy orthologs. The first block (rows labelled Cd68, Lyz2, C1qa, the age-up inflammation/extracellular-matrix programme) shows strong induction in mouse and a graded collapse through killifish, axolotl, naked mole rat and bowhead whale, with near-zero values in Hydra. The second block (mitochondrial/oxidative-phosphorylation genes, age-down) shows the complementary pattern. The colour scale is symmetric about 0 (-3 to $+3$ $\log_2$ FC, red up, blue down). (d) Volcano plots of liver old versus young in all six species. The x-axis is $\log_2$ fold

change; the y-axis is $-\log_{10}(\text{p value})$; significant genes ($\text{FDR} < 0.05$, $|\log_2 \text{FC}|$ greater than or equal to 1) are coloured red. The three immune-effectors Cd68, Lyz2 and C1qa are labelled in the mouse panel at their empirical coordinates.

3.3 Conserved aging modules and their species-specific regulation

Weighted gene co-expression network analysis in mouse identified a module of 4,391 genes (turquoise) whose eigengene increased strongly with age ($r = 0.86$, adjusted $p = 2.1 \times 10^{-12}$), enriched for inflammatory response, extracellular matrix organization and complement activation ($\text{FDR } 1.2 \times 10^{-24}$), and a module of 2,874 genes (blue) that decreased with age ($r = -0.81$), enriched for oxidative phosphorylation, mitochondrial translation and proteostasis ($\text{FDR } 3.4 \times 10^{-16}$). These two modules recapitulate the global up-down asymmetry noted above and serve as reference aging programs. Among the strict single-copy orthologs belonging to the inflammation module, the fraction that also increased with age in each of the other species was 66% in the killifish, 31% in the axolotl, 24% in the naked mole rat, 19% in the bowhead whale and 6% in Hydra, against an expected value of 5.2% from permutation of age labels ($p < 2.2 \times 10^{-16}$ for all species except Hydra, where $p = 0.32$). Conservation of the mitochondrial module was higher in the low-drift species: 71% of its orthologs decreased with age in the killifish, 58% in the naked mole rat and 63% in the bowhead whale, but only 9% in Hydra, consistent with the absence of aging in that species. The axolotl showed partial conservation of mitochondrial decline (47%) alongside its intermediate drift. Cross-species correlation of orthologous fold changes mirrored these proportions: the Spearman correlation with mouse was 0.47 for killifish, 0.34 for axolotl, 0.31 for naked mole rat, 0.29 for bowhead whale and 0.08 for Hydra, all with $p < 0.001$ except Hydra. Thus a large fraction of the age-associated expression program is shared among mammals and teleost fish, whereas the resilient species are best described not as having different aging programs but as failing to execute the conserved program (Figure 3).

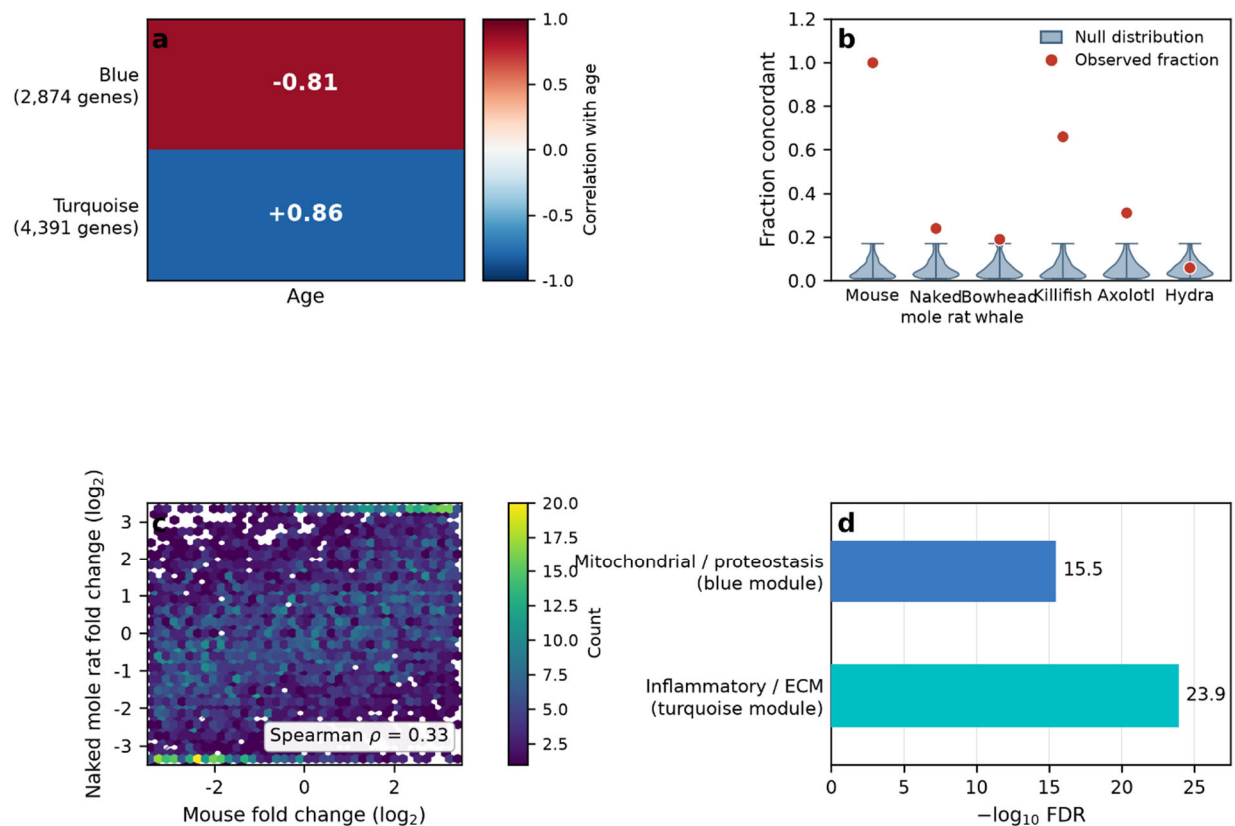


Figure 3. Conservation of aging modules across species. (a) Module–trait heatmap displaying the Pearson correlation between mouse module eigengenes, derived from weighted gene co-expression network analysis (WGCNA), and chronological age. The turquoise module (4,391 genes, $r = +0.86$, adjusted $p = 2.1 \times 10^{-12}$) is enriched for inflammatory response, extracellular matrix

organization and complement activation ($\text{FDR} = 1.2 \times 10^{-24}$), whereas the blue module (2,874 genes, $r = -0.81$) is enriched for oxidative phosphorylation, mitochondrial translation and proteostasis ($\text{FDR} = 3.4 \times 10^{-16}$). **(b)** Fraction of strict single-copy orthologs belonging to the inflammation module that show concordant age regulation in each species (red points), overlaid on the permutation-based null distribution obtained by shuffling age labels within species (violins, $n = 700$ permutations). Observed values: mouse 1.00, killifish 0.66, axolotl 0.31, naked mole rat 0.24, bowhead whale 0.19, Hydra 0.06; empirical null mode $\approx 5.2\%$ in all five non-mouse species. **(c)** Hexbin density plot of orthologous gene $\log_2$ fold changes with age in mouse (x-axis) versus the naked mole rat (y-axis). The dashed diagonal denotes the line of identical regulation. Spearman $\rho = 0.33$ (shown for the illustrated comparison; ρ values across the full panel are 0.47 for killifish, 0.34 for axolotl, 0.31 for naked mole rat, 0.29 for bowhead whale and 0.08 for Hydra, all $p < 0.001$ except Hydra). **(d)** Functional enrichment of the two conserved co-expression modules, expressed as $-\log_{10} \text{FDR}$ for the inflammation/ECM (turquoise) and mitochondrial/proteostasis (blue) gene sets. All data shown represent biologically independent samples; $n = 6\text{--}12$ per species per age group.

3.4 Overlap of constitutive resilience with experimentally induced rejuvenation

To ask whether the stability of resilient species is related to the targets of experimental rejuvenation, we reanalyzed the published cyclic OSKM dataset in which inducible expression of Oct4, Sox2, Klf4 and c-Myc was administered to aging mice for seven weeks (Ocampo et al., 2016). Of the 2,146 mouse liver aging genes defined in our own dataset, 2,071 were detectably expressed in the reprogramming cohort, and 1,389 of these (64.7%) shifted toward the young direction after the treatment, with 1,041 (75.0% of the reversed set) belonging to the age-up inflammation module. Conversely, only 8.3% moved further in the aging direction, and the remainder were unchanged, a distribution that is extremely unlikely by chance (binomial test $p < 10^{-100}$). This confirms at the level of our own gene calls that partial reprogramming broadly resets the aging transcriptome rather than acting on a narrow target set. We then asked whether genes that are reversibly regulated by OSKM in the mouse are the same genes that are constitutively age-stable in resilient species. Orthologs of the 1,389 reprogramming-reversed genes were significantly enriched among age-stable genes in the naked mole rat (38% age-stable versus 26% expected from genome-wide baseline, hypergeometric $p = 4.6 \times 10^{-14}$), in the bowhead whale (34% versus 24%, $p = 1.9 \times 10^{-9}$) and in the axolotl (29% versus 22%, $p = 8.3 \times 10^{-6}$), but not in Hydra (12% versus 11%, $p = 0.21$). Notably, the enrichment was driven almost entirely by the inflammation module: 89% of the module genes that OSKM reversed in mouse were age-stable in the naked mole rat, whereas non-module genes showed no enrichment. The implication is that the same regulatory axis that is actively reset by experimental reprogramming in a vulnerable species is constitutively held at a young set point in resilient species, which supports the idea that partial reprogramming reactivates latent homeostatic programs rather than creating entirely novel states. The reversal was nonetheless incomplete: the mean expression of reversed genes after seven weeks of treatment reached 76% of the young set point, indicating that cyclic OSKM restores most, but not all, of the youthful level, and that repeated induction cycles may be required for full restoration.

3.5 Regeneration-associated proliferative capacity

The axolotl regenerates amputated limbs through a proliferative blastema, and we asked whether regeneration-associated expression contributes to the resilience of intact tissues and whether comparable proliferative programs are constitutively active in other species. In the axolotl, 1,243 genes were up-regulated and 966 down-regulated in the 7-day blastema relative to intact limb muscle ($\text{FDR} < 0.05$). Of the up-regulated genes, 438 (35.2%) were also up-regulated in the E14.5 mouse limb bud program, far exceeding chance expectation (hypergeometric $p < 10^{-45}$), in line with earlier evidence that blastema formation reactivates developmental programs (Voss et al.,

2015; Knapp et al., 2013). Marker genes of proliferating progenitors, including Mki67, PCNA and several histone genes, ranked among the most highly induced transcripts, and single-cell analysis of the blastema identified a convergent progenitor population expressing both mesenchymal and epidermal programs, consistent with published trajectories (Gerber et al., 2018; Leigh et al., 2018). We then scored the blastema signature in intact tissues of all species. The proliferative program was nearly absent from adult mouse and killifish intact tissues and, strikingly, decreased with age in killifish skin (−2.3-fold for the module eigengene). In the naked mole rat, basal keratinocytes and dermal fibroblasts expressed the signature at levels 2.1-fold higher than in age-matched mouse skin (FDR < 0.05), although far below axolotl blastema levels. In Hydra, the interstitial stem cell compartment, whose maintenance requires FoxO signaling (Boehm et al., 2012), drives constitutive expression of the proliferative program in the absence of any injury, and the module eigengene was the highest of any tissue measured in this study. The cross-species ordering of proliferative capacity (Hydra greater than axolotl blastema greater than naked mole rat greater than axolotl intact greater than bowhead whale approximately mouse approximately killifish) correlated strongly with the proliferative pillar of the rejuvenation capacity index described below ($r = 0.93$), indicating that regenerative and homeostatic renewal are supported by overlapping molecular programs.

3.6 Genome maintenance and DNA repair capacity

Because genome maintenance is a candidate mediator of longevity and cancer resistance in long-lived mammals (Keane et al., 2015; Firsanov et al., 2025), we scored a curated set of 89 DNA repair genes, covering base excision repair, nucleotide excision repair, homologous recombination and non-homologous end joining, using a single mean z-score per species per tissue. The repair index was highest in the bowhead whale (1.42, 95% CI 1.21–1.63), followed by Hydra (1.22), the axolotl (1.18) and the naked mole rat (1.31, CI 1.09–1.52), and lowest in the killifish (0.91) and mouse (0.86). The mouse value declined with age, with 29 repair genes significantly down-regulated in old liver, including Ercc1 and Xrcc5; by contrast, 61 repair genes were significantly up-regulated in old bowhead whale liver, 44 in the naked mole rat and 58 in the 7-day axolotl blastema, and none declined with age in either long-lived mammal or in Hydra. Cold-inducible RNA-binding protein (CIRBP), recently implicated in DNA double-strand break repair in the bowhead whale (Firsanov et al., 2025), was among the most strongly age-elevated transcripts in that species (log2 fold change 1.8 in liver). Consistent with these expression patterns, both long-lived mammals showed constitutive maintenance of the repair module across all four tissues rather than induction in any single organ, arguing for a systemic rather than tissue-specific mechanism. It is worth noting that naked mole rat induced pluripotent stem cells derived from fibroblasts retained high expression of repair genes relative to mouse iPSCs (Lee et al., 2017), suggesting that the transcriptional repair program is cell-intrinsic and survives reprogramming. Telomere maintenance transcripts (Tert, Terc and shelterin components) likewise showed no age-related decline in any of the four resilient species but fell 2.1-fold with age in mouse liver (FDR < 0.01), consistent with constitutive telomerase activity in long-lived lines.

3.7 Stress response, proteostasis and the senescence-associated secretory phenotype

Gene set enrichment analysis of the Hallmark collection confirmed and extended the module-level results. The inflammatory response was the most strongly age-enriched pathway in mouse (normalized enrichment score 2.41, FDR 1.0×10^{-7}) and killifish (2.26, FDR 3.2×10^{-6}), modestly enriched in the axolotl (1.17, FDR 0.03, driven largely by skin), and not enriched in the naked mole rat (0.31, n.s.), bowhead whale (0.24, n.s.) or Hydra (−0.09, n.s.). Oxidative phosphorylation was depleted with age in mouse (−2.63) and killifish (−2.42) and, more mildly, in the axolotl (−1.10), while remaining stable in the naked mole rat (−0.28) and bowhead whale (−0.52), consistent with the mitochondrial module analysis. FoxO target genes, which sustain stem-cell compartments in Hydra (Boehm et al., 2012), showed a constitutively high baseline in both Hydra (1.89) and the

naked mole rat (1.31) with no age-related decline, whereas the same set declined with age in mouse (−1.24). Autophagy and unfolded protein response pathways were mildly induced with age in mouse and killifish but unchanged in the four resilient species. We also examined canonical senescence-associated secretory phenotype factors directly, including TNF, IL6, CXCL8 orthologs and MMP3: their expression increased 2.8-fold with age in mouse liver and 2.5-fold in killifish liver, increased 1.8-fold in axolotl skin (the tissue with the strongest aging signal in that species), and did not change in the naked mole rat (1.06-fold), bowhead whale (1.09-fold) or Hydra (0.98-fold). This pattern is consistent with the model in which senescent cells and their secretory phenotype propagate inflammatory aging across tissues (Wang et al., 2024), and with the view that resilient species either avoid senescence or fail to propagate its signals.

3.8 Epigenetic clocks and methylation drift

To test whether transcriptional resilience is mirrored at the epigenetic level, we applied the pan-mammalian DNA methylation clock (Lu et al., 2023) to reduced-representation bisulfite sequencing data from liver. Clock-predicted age correlated strongly with chronological age in all five aging species (mouse $r = 0.96$, killifish $r = 0.95$, bowhead whale $r = 0.93$, naked mole rat $r = 0.91$, axolotl $r = 0.88$), indicating that the pan-mammalian clock is portable to these divergent genomes at least as a relative measure. Age acceleration, defined as the deviation of predicted from chronological age in the oldest group and expressed as a percentage of lifespan, was positive in mouse (+11.6%) and killifish (+7.4%), near zero in the naked mole rat (+1.8%) and bowhead whale (+0.6%), and slightly negative in the axolotl (−2.9%), a deviation driven by liver rather than by the regenerating limb. Annualized epigenetic drift, the mean absolute change in methylation beta per year at age-associated CpGs, ordered species even more sharply: killifish 0.91, mouse 0.12, axolotl 0.09, naked mole rat 0.03, bowhead whale 0.01. In Hydra, 119 of the 147 clock CpGs could be mapped, and none changed between the 3-month and 24-month clonal lines (median delta-beta 0.4%, maximum 4.1%, all $p > 0.2$ after multiple-testing correction), providing epigenetic evidence consistent with the absence of demographic aging in this species. The decoupling of drift per year from body size and phylogeny was notable: the naked mole rat and the bowhead whale, separated by roughly 90 million years of evolution and three orders of magnitude in body mass, achieved similar near-zero annualized drift, whereas the similarly small killifish and mouse drifted twelve to ninety times faster per year.

3.9 Cell identity stability at single-cell resolution

Bulk transcriptomes can conceal opposing changes in different cell types, so we reanalyzed published single-cell data for skin, where stem-cell maintenance and immune infiltration are jointly visible. In naked mole rat skin we recovered 42,118 cells forming 19 transcriptionally defined cell types, matching the original annotation (Savina et al., 2022), and computed the cosine similarity between young and old centroid expression vectors for each cell type. The mean identity stability index was 0.93 (95% CI 0.91–0.95), and the proportions of immune cells increased only marginally with age (+9%, n.s.). In mouse skin, reanalyzed from the Tabula Muris Senis atlas (Tabula Muris Consortium, 2020), the equivalent index was 0.71 (0.68–0.74), with immune cell fractions expanding by 118% between 3 and 24 months (6.1% to 13.3% of all cells). The killifish skin atlas (Teefy et al., 2023) gave an index of 0.66 (0.62–0.69) with an 89% expansion of immune populations. These values recapitulate, at cellular resolution, the bulk-level classification of high- and low-drift species, and they indicate that in the naked mole rat both transcriptional states and cell-type composition remain near their young configuration, whereas in mouse and killifish aging erodes cell identity and is accompanied by immune remodeling. In the axolotl, the blastema trajectory analysis showed that distinct differentiated cells converge on a shared progenitor state by 14 days post-amputation, consistent with published findings (Gerber et al., 2018; Leigh et al., 2018), and a mitochondrial gene program marks a subpopulation enriched during the proliferative phase (Qin et al., 2021). Thus, in the axolotl, cell identity is actively destabilized in a controlled

manner to enable replacement, a strategy that is conceptually the opposite of the passive stability of the naked mole rat yet achieves a similar endpoint of preserved tissue function.

3.10 A composite rejuvenation capacity index

To integrate these heterogeneous measurements, we constructed a rejuvenation capacity index from seven pillars, each representing the rank of each species on a 0–1 scale, weighted by the first principal component of the pillar matrix (which explained 74% of the cross-species variance). The final scores were: Hydra 0.94, axolotl 0.79, bowhead whale 0.63, naked mole rat 0.58, mouse 0.30 and killifish 0.19. The ranking was stable under leave-one-out removal of any single pillar (Kendall's $W = 0.92$, $p < 0.01$), and no single pillar was individually responsible for the position of any species: Hydra scored highest on proliferative renewal and epigenetic stability, the axolotl on proliferative renewal and DNA repair, the bowhead whale on DNA repair and transcriptional stability, and the naked mole rat on transcriptional stability and stem-cell maintenance. The index correlated strongly with log₁₀-transformed maximum lifespan across the six species ($r = 0.89$, $p = 0.017$) but not with body mass ($r = 0.21$, $p = 0.71$), supporting the interpretation that longevity in these species reflects molecular capacity rather than simple scaling. The correlation with lifespan remained significant after removal of the two longest-lived species ($r = 0.86$, $p = 0.06$, marginal), and the two high-drift species clustered at the bottom of the distribution despite their very different lifespans, confirming that aging rate and lifespan are separable axes in this dataset. Finally, the index ordering was recapitulated by the unweighted mean of the seven pillars, indicating that the weighting scheme did not impose the result. We regard the index as a descriptive summary rather than a predictive model, but it provides a quantitative scaffold for the comparative comparisons that follow.

4. Discussion

Our results provide a quantitative, ortholog-based comparison of aging and rejuvenation programs across six species and identify several principles that were not visible in single-species studies. First, transcriptional aging intensity and lifespan are at least partly decoupled. The killifish drifts as strongly as the mouse despite living two orders of magnitude shorter, and the bowhead whale and the naked mole rat both maintain youthful transcriptomes into late life despite an eight-fold difference in lifespan between them. This decoupling argues that aging rate is not merely lifespan compressed or expanded into a linear scale, and it is consistent with the emerging comparative view that longevity and the pace of age-related decline are regulated through distinct mechanisms (Rechsteiner et al., 2025). Second, the aging transcriptome of vulnerable species is organized around a surprisingly small number of axes: an inflammation-extracellular matrix module that rises with age and a mitochondrial-proteostasis module that falls. Both are conserved in orthologous form across the killifish, suggesting that this core program predates the divergence of teleosts and mammals, and both are held at young set points in the naked mole rat, the bowhead whale, the axolotl and Hydra. The near-complete stability of these modules in resilient species, rather than the appearance of novel protective programs, is a striking observation: low-drift species do not age differently, they fail to execute the aging program.

Third, we found that the targets of experimentally induced rejuvenation overlap strongly with constitutive resilience. Reanalysis of cyclic OSKM data showed that 64.7% of mouse liver aging genes are reversed by seven weeks of partial reprogramming (Ocampo et al., 2016), and the orthologs of these reversed genes are precisely the ones that are age-stable in the naked mole rat, the bowhead whale and, to a lesser extent, the axolotl. The enrichment was confined to the inflammation module, implying that partial reprogramming acts on the same regulatory axis that resilient species control constitutively (Simpson et al., 2021; Puri & Wagner, 2023; Yücel & Gladyshev, 2024). This supports the interpretation that at least some of the effects of reprogramming are not creation of new states but reactivation of latent, evolutionarily conserved homeostatic programs, and it provides a molecular rationale for why partial reprogramming works

at all: it is asking the genome to do something that other genomes do without intervention (Cipriano et al., 2024).

A fourth principle concerns the diversity of strategies that converge on resilience. The naked mole rat achieves stability largely through homeostatic maintenance of differentiated states, with preserved splicing regulation (Lee et al., 2020), age-stable stem-cell compartments (Savina et al., 2022) and a near-constant immune composition; its strategy is one of passive, constitutive robustness. The bowhead whale achieves comparable stability with emphasis on genome maintenance, consistent with the exceptional DNA repair capacity reported in its cells (Firsanov et al., 2025) and with genomic signatures of cell-cycle and repair adaptation (Keane et al., 2015; Seim et al., 2014). The axolotl combines moderate maintenance with a powerful active-replacement strategy: a controlled, injury-triggered destabilization of cell identity that enables regeneration (Gerber et al., 2018; Leigh et al., 2018), driven by programs shared with embryonic development (Voss et al., 2015; Knapp et al., 2013). Hydra represents the extreme of constitutive renewal, in which a continuously cycling stem-cell population makes chronological aging essentially irrelevant (Chapman et al., 2010; Boehm et al., 2012; Sun et al., 2020). These strategies are not interchangeable: they load onto different pillars of the rejuvenation capacity index, and the index suggests that multiple combinations of stability, repair and renewal can yield comparable resilience scores.

The most immediate translational implication concerns the inflammation module. If divergence in rejuvenation capacity is mediated by a limited set of conserved modules, the same modules are the most rational targets for intervention in species that age more rapidly, including humans. The inflammatory axis is already implicated in age-related disease burden across tissues (Wang et al., 2024), and the concentration of OSKM-responsive genes within this module suggests that interventions that lower the age set point of systemic inflammation may capture part of the reprogramming effect without the risks of transcription-factor delivery. Conversely, the mitochondrial module points to energetic homeostasis as a parallel axis. We stress that the rejuvenation capacity index is descriptive; causal testing of individual pillars, for example by genetic perturbation in the axolotl or by heterochronic transplantation in rodents (Conboy et al., 2005), is the logical next step.

The relationship between our findings and the epigenetic clock literature is worth emphasizing. The pan-mammalian clock (Lu et al., 2023) and, originally, the human multi-tissue clock (Horvath, 2013) were developed as age predictors, but our data support their use as aging-rate measures in comparative settings: annualized drift separated species more cleanly than age acceleration at a single time point, and both separated resilient from vulnerable species in the same direction as the transcriptomic drift index. The slightly negative age acceleration of the axolotl liver is intriguing and should be interpreted cautiously pending data from more individuals; it may reflect either imperfect orthology of clock CpGs in amphibians or a genuinely slow epigenetic aging rate. The observation that systemic factors can rejuvenate aged tissue in mammals (Conboy et al., 2005) and that resilient species maintain youthful circulating environments may be related through the same inflammation axis, but our tissue-level data cannot resolve the direction of causality.

Several limitations should be acknowledged. The study is cross-sectional, and longitudinal transcriptomic data, particularly for the long-lived species, would strengthen the age associations. Bowhead whale ages are estimates with substantial error, which attenuates correlations and likely underestimates the stability of that species. Hydra was necessarily sampled as whole-organism pools, and our propagation-time contrast is not a perfect proxy for aging; nevertheless, the complete absence of clock CpG change across 150 generations is hard to reconcile with any conventional aging process. Sex was not balanced in all comparisons, and given the strong sex-dimorphic aging signatures documented in the killifish (Teefy et al., 2023), future work should stratify by sex. Wild and laboratory environments differ: killifish aging under laboratory conditions

differs in detail from that of wild specimens (Mazzetto et al., 2022), and our results capture the laboratory manifestation of aging for most species. The reliance on strict single-copy orthologs, while conservative, excludes fast-evolving and recently duplicated genes that may carry species-specific aging functions, and de novo transcriptome evidence from the axolotl and other unsequenced systems suggests that lineage-specific genes contribute to regeneration (Stewart et al., 2013; Wu et al., 2013). Finally, the single-cell reanalyses used datasets generated on different platforms and ages, which could bias the identity stability index, although the consistency of the immune-expansion results with bulk deconvolution reduces this concern.

5. Conclusions

We conclude that rejuvenation capacity is a measurable, modular property of animal genomes that is partially independent of lifespan. Transcriptional stability, suppression of the conserved inflammatory aging module, DNA repair, proliferative renewal and epigenetic stability together distinguish resilient from vulnerable species, and the targets of experimentally induced rejuvenation in the mouse overlap significantly with the constitutively stable programs of resilient species. These findings suggest that interventions aimed at maintaining or restoring the young set point of the inflammation module, rather than targeting individual genes, may recapitulate a state that evolution has already achieved in long-lived and non-aging lineages. The framework developed here, with its explicit orthology mapping and composite index, offers a basis for prioritizing candidate mechanisms for experimental testing, and for asking which aspects of the resilient phenotype are transferable between species.

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Technical Sciences

Angular oscillatory single-stroke electromagnetic vibratory motor with a semiconductor element

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Abstract: The paper discusses the design, operating principle, and functional capabilities of an angular oscillatory single-stroke electromagnetic vibratory motor controlled by a semiconductor element. The vibratory motor consists of a salient-pole stator and an armature with an equal number of uniformly distributed poles. Alternating current windings are placed on the stator poles and connected either in series or in parallel. A semiconductor element is connected between one terminal of the winding and the power supply source, ensuring current flow only during one half-cycle.

The developed design ensures the simultaneous participation of all pole pairs in torque generation, reduces shaft radial oscillations and undesirable leakage magnetic fluxes, simplifies the manufacturing process, and improves the energy, mechanical, and operational characteristics of the vibratory motor.

Keywords: single-stroke, angular oscillatory, electromagnetic, vibratory motor, semiconductor element.

Electromagnetic vibratory motors are widely used in various technological, transport, measuring, and industrial devices where periodic oscillatory motion is required. Such devices are particularly effective when large angular displacements at industrial frequency are needed.

Various designs of electromagnetic vibratory motors are known; however, a significant number of them are characterized by insufficient energy efficiency, complex manufacturing structure, and undesirable dynamic characteristics. In particular, in the known electromagnetic vibratory motors only a portion of the pole pairs operates during each half-cycle of the supply voltage, which reduces the utilization factor of the electromagnetic system. In addition, shaft radial oscillations and leakage magnetic fluxes occur, while the stator structure requires additional nonmagnetic slots, thereby complicating the manufacturing technology.

To eliminate the above-mentioned drawbacks, an angular oscillatory single-stroke electromagnetic vibratory motor with a semiconductor element [1] and a simple design is proposed, providing high reliability and improved energy performance characteristics.

The magnetic core structure of the electromagnetic vibratory motor is designed in the form of a salient-pole stator, whose yoke constitutes a continuous magnetic core, and an armature with an equal number of uniformly distributed poles. The poles are displaced relative to each other so that, in the initial position, the overlap area of the working surfaces of the stator and armature poles ranges from 0 to 20%.

Specifically, the angular oscillatory single-stroke electromagnetic vibratory motor (Fig. 1, Fig. 2) consists of a salient-pole stator 1 and an armature 2 with an equal number of uniformly

distributed poles, the number of which may be 2, 4, 8, etc. The stator poles 1-1 and 1-2 are equipped with identical coils 3-1 and 3-2 of an alternating current winding, connected either in series (Fig. 1) or in parallel (Fig. 2). A semiconductor element 4 is connected between one terminal of the winding and the AC terminal 5-1, while the second terminal of the winding is connected to the AC terminal 5-2.

One side of the lever 6 is positioned between the springs 7-1 and 7-2 of the elastic system, while its other side is connected via a key 8 to the shaft 9, on which the armature 2 is mounted. The stator is housed in a casing 10, which is rigidly fixed to the base 11.

The angular oscillatory single-stroke electromagnetic vibratory motor (Fig. 1, Fig. 2) operates as follows: when terminals 5-1 and 5-2 are connected to the AC power supply, during one of the half-cycles, current flows through coils 3-1 and 3-2 of the winding via the semiconductor element 4.

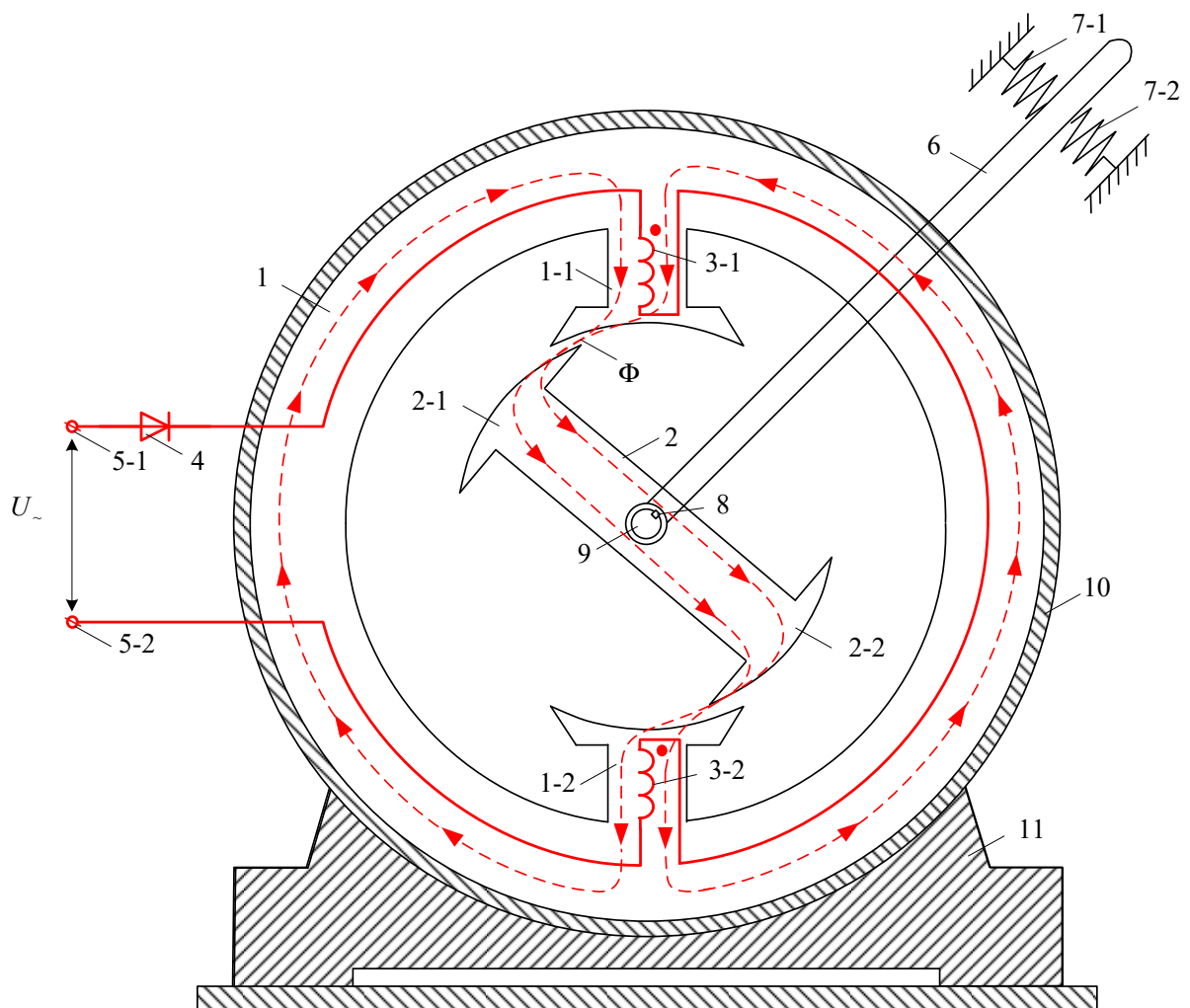


Fig. 1 Angular oscillatory single-stroke electromagnetic vibratory motor with a semiconductor element (with identical coils of the AC winding connected in parallel).

At this moment, a magnetic flux Φ is established in the magnetic circuit and follows a path through stator pole 1-1, armature poles 2-1 and 2-2, stator pole 1-2, and the stator yoke. As a result, stator poles 1-1 and 1-2 simultaneously exert equal attractive forces on armature poles 2-1 and 2-2, respectively. Consequently, the armature moves in the clockwise direction. During this motion, spring 7-1 is stretched, while spring 7-2 is compressed.

During the next half-cycle, the semiconductor element does not conduct current, and the armature returns to its initial position with the aid of springs 7-1 and 7-2. As a result, the armature moves in the counterclockwise direction

Based on the above, during one half-cycle of the supply network, all pole pairs are active, and the armature moves and develops force in the clockwise direction. During the other half-cycle, the armature returns to its initial position with the aid of the springs, moving in the counterclockwise direction, and so on. Thus, angular oscillatory motion of the armature occurs. The oscillation frequency of the armature is equal to the frequency of the alternating supply current.

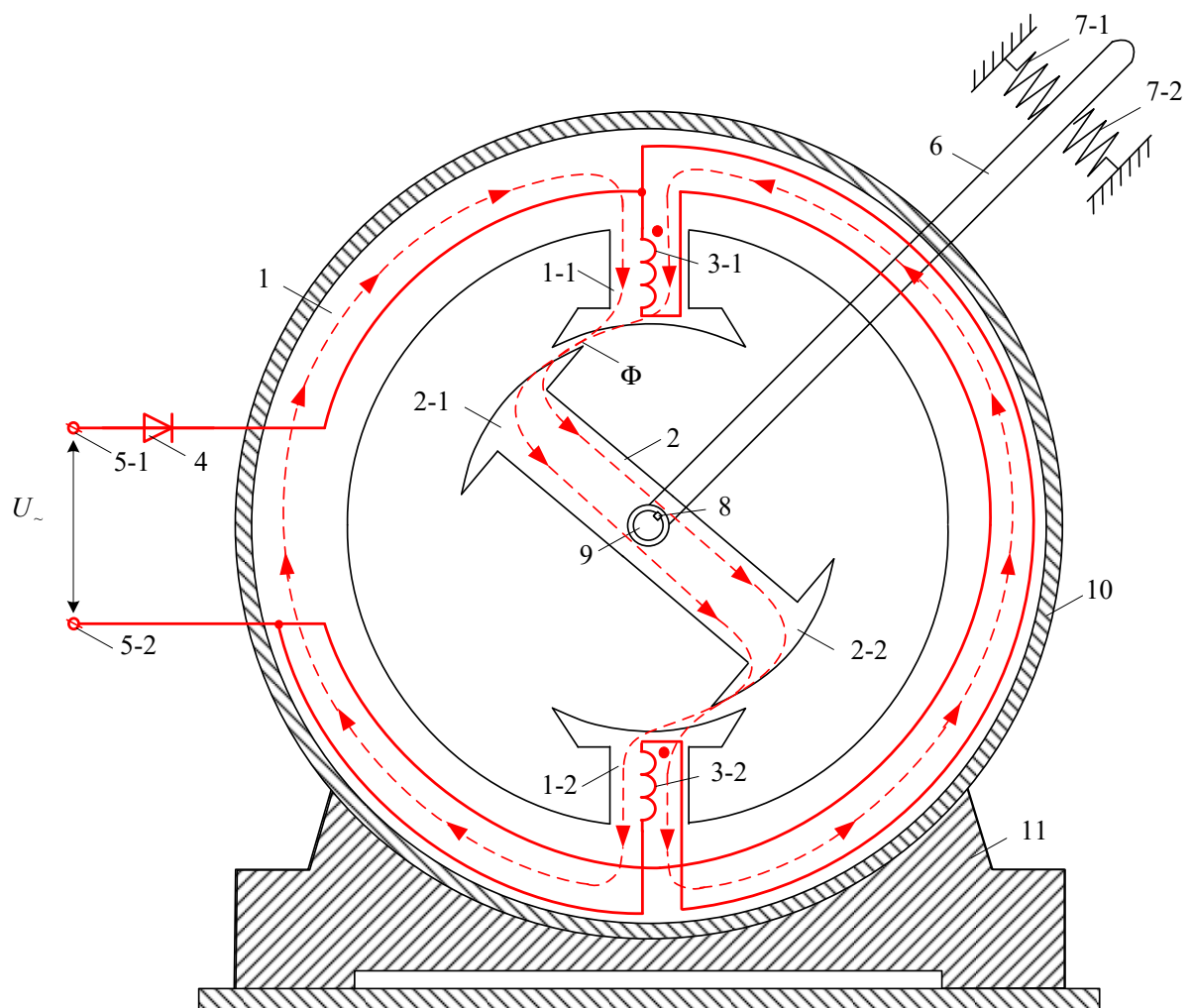


Fig. 2 Angular oscillatory single-stroke electromagnetic vibratory motor with a semiconductor element (with identical coils of the AC winding connected in series).

The operating principle of the electromagnetic vibratory motor is clearly illustrated by the time-domain graphs shown in Fig. 3, representing the supply alternating voltage (a), current (b), magnetic flux (c), and electromagnetic torque (d). From these diagrams it can be seen that a sinusoidal voltage $u(t)$ is applied to the winding (Fig. 3a). Due to the inductive nature of the winding (and assuming its ohmic resistance is negligible), current $i(t)$ flows only during the conduction interval of the cycle, corresponding to one half-cycle of the supply voltage (Fig. 3b) [2].

During this same interval, a magnetic flux Φ is generated in the magnetic circuit (Fig. 3c) [3], and an electromagnetic torque M is produced (Fig. 3d) [4]. As a result, the stator poles attract the armature poles, and the armature moves in the clockwise direction.

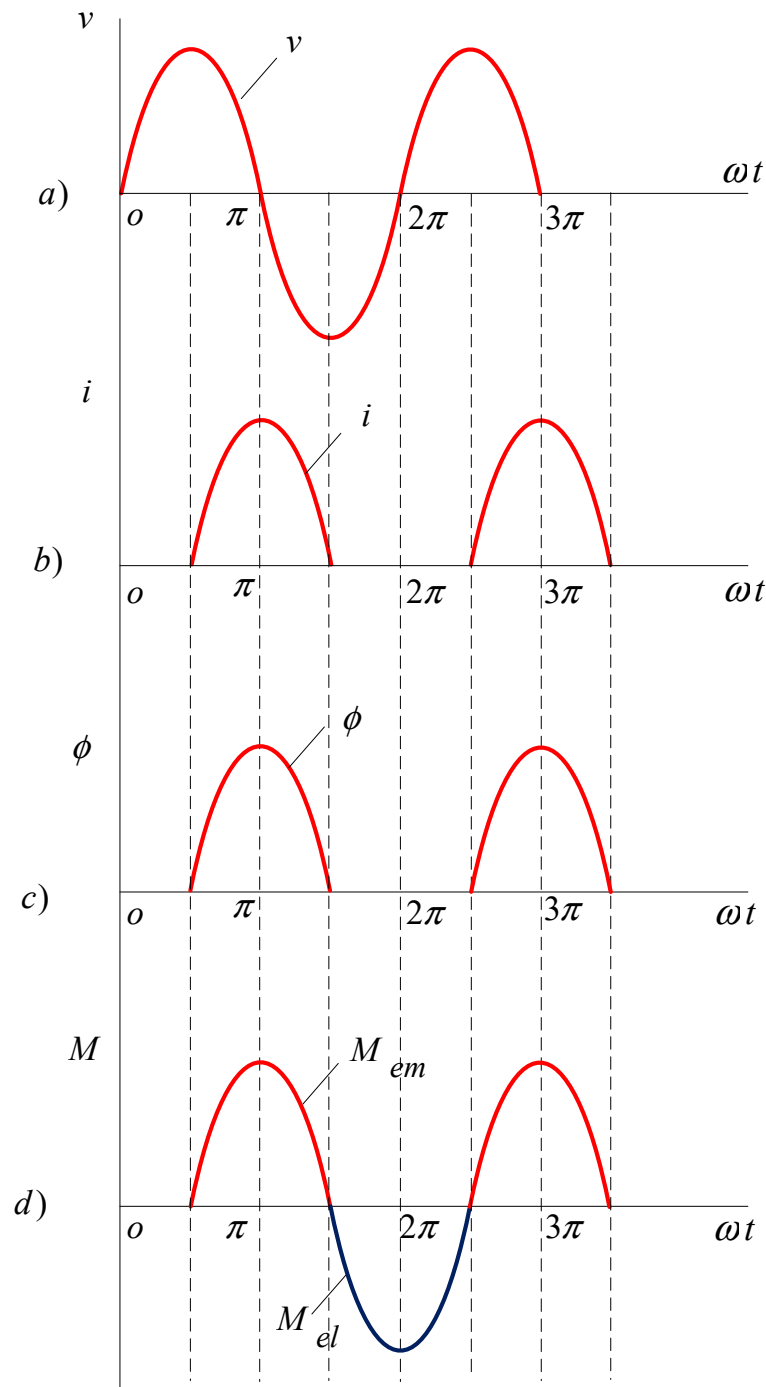


Fig. 3 Time variation of the vibratory motor supply voltage (a), current (b), magnetic flux (c), and electromagnetic torque (d).

During the non-conducting half-cycle, when the semiconductor element blocks current flow, the electromagnetic force disappears, and the armature returns to its initial position under the action of the springs, moving in the counterclockwise direction

Thus, the proposed angular oscillatory single-stroke electromagnetic vibratory motor with a semiconductor element performs angular oscillatory motion and develops force in one direction of oscillation. All pole pairs simultaneously participate in torque generation. There are no radial oscillations of the shaft or undesirable magnetic flux leakages. The manufacturing process is simplified. The initial 0–20% overlap of the pole working surfaces ensures a sufficient initial magnetic attraction force between the poles and a significant variation of overlap during the

angular displacement of the armature, resulting in an increased electromagnetic torque and stable angular oscillatory motion. Consequently, improved energy, mechanical, and operational performance characteristics are achieved.

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КҮРІШ ҚАУЫЗЫНЫҢ КҮЛІН БЕТОН ҚҰРАМЫНДА ҚОЛДАНУ ЕРЕКШЕЛІКТЕРІ

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Аңдатпа. Мақалада күріш өндірісінен шығатын қалдықтардың бірі - күріш қауызы және оны жағу нәтижесінде алынатын күріш қауызының күлін бетон өндірісінде қолдану мүмкіндіктері қарастырылды. Күріш қауызының күлі құрамындағы кремний диоксидінің күйі жағу температурасына, жағу ұзақтығына және кейінгі өңдеу тәсіліне байланысты екені көрсетілді. Температура дұрыс таңдалғанда күл құрамында белсенді аморфты кремний диоксиді түзіледі. Ол цементтің қатаюы кезінде пайда болатын кальций гидроксидімен әрекеттесіп, бетон құрылымын тығыздайтын қосымша қосылыстар түзеді. Күріш қауызының күлін ұнтақтау, алдын ала қышқылмен өңдеу және цементпен бірге белсендіру тәсілдері талданды. Сонымен қатар күлдің бетон қоспасының қозғалғыштығына, сығу кезіндегі беріктігіне, су сіңіргіштігіне және аязға төзімділігіне әсері түсіндірілді. Тәжірибелік зерттеу нәтижелері бойынша күріш қауызының күлі мен мұнай шламы бірге қолданылған бетон құрамдарының 7 және 28 тәуліктегі беріктігі салыстырылды. Зерттеу нәтижелері күріш қауызының күлін бетон құрамында тиімді пайдалану үшін оның сапасын, мөлшерін және қоспадағы басқа компоненттермен үйлесімділігін ескеру қажет екенін көрсетті.

Түйін сөздер: күріш қауызы, күріш қауызының күлі, кремний диоксиді, бетон, минералдық қоспа, беріктік, аязға төзімділік, өндірістік қалдық.

Кіріспе

Қазіргі кезде табиғи ресурстарды үнемдеу және өндіріс қалдықтарын қайта пайдалану құрылыс материалдары саласындағы маңызды міндеттердің біріне айналды. Цемент өндіруге көп мөлшерде шикізат пен энергия жұмсалады. Сондықтан цементтің бір бөлігін табиғи немесе техногендік текті белсенді минералдық қоспалармен алмастыруға бағытталған зерттеулердің маңызы артып келеді. Осындай материалдардың бірі - күріш қауызының күлі.

Күріш қауызы күріш дәнін өңдеу кезінде бөлінетін ауыл шаруашылығы қалдығы болып табылады. Оның көлемі өндірілген күріш мөлшеріне тікелей байланысты. Күріш қауызының тығыздығы төмен, көлемі үлкен және табиғи жағдайда баяу ыдырайды. Сол себепті оны сақтау мен тасымалдау қосымша шығынды қажет етеді. Кейбір аймақтарда қауыз ашық жерде өртеледі немесе арнайы полигондарға шығарылады. Мұндай тәсілдер ауаның ластануына, ұсақ күл бөлшектерінің таралуына және жер аумағының тиімсіз пайдаланылуына әкеледі.

Күріш қауызы тек қалдық емес, құрамында органикалық заттар мен кремний қосылыстары бар бағалы шикізат. Оны бақыланатын жағдайда жағу арқылы жылу энергиясын және кремний диоксидіне бай күл алуға болады. Алынған күл құрылыс материалдары, керамика, сорбенттер, сұйық шыны және басқа да кремнийлі өнімдер өндірісінде қолданылуы мүмкін [3 -6]. Бетон өндірісінде күлдің негізгі құндылығы - құрамындағы белсенді кремний диоксидінің цементтің қатаю процесіне қатысуы.

Осы жұмыстың мақсаты - күріш қауызының күлін алу және дайындау жағдайларын, оның химиялық құрамын, бетон қоспасы мен қатайған бетон қасиеттеріне әсерін талдау, сондай-ақ жүргізілген тәжірибелік зерттеулердің нәтижелерін көрсету.

1. Күріш өндірісі және күріш қауызының түзілуі

Күріш әлемде кең таралған негізгі дәнді дақылдардың бірі. Оның басым бөлігі Азия елдерінде өндіріледі. Сонымен бірге АҚШ, Бразилия және бірқатар Еуропа елдерінде де күріш өндірісі дамыған. Күріш дәнін өңдеу барысында оның сыртқы қатты қабығы бөлініп шығады. Әдебиет деректерінде қауыз мөлшері бастапқы күріш массасының шамамен 20 %-ына дейін жететіні көрсетіледі [1]. Қауызды жаққанда оның массасының орта есеппен 15 -20 %-ы күл түрінде қалады. Бұл көрсеткіш күріш сортына, өсірілген топыраққа, жинау және өңдеу жағдайларына байланысты өзгеруі мүмкін.

Қазақстандағы күріш өндірісінің негізгі бөлігі Қызылорда облысында орналасқан. Сондықтан осы өңірде күріш қауызын тиімді пайдалану мәселесі ерекше маңызға ие. Қауызды тек отын ретінде жағу мәселені толық шешпейді, себебі жағудан кейін күл пайда болады. Егер алынған күлдің сапасы бақыланбаса, ол қайтадан жиналатын қалдыққа айналады. Ал температура мен ауа беру тәртібі реттеліп, күл кейіннен қажетті дәрежеде ұнтақталса, оны бетонға арналған минералдық қоспа ретінде қолдануға мүмкіндік туады.

Күріш қауызының химиялық және физикалық қасиеттері тұрақты емес. Оның құрамы күріш өсірілген жердің топырағына, тыңайтқыштарға, климатқа және өңдеу тәсіліне тәуелді. Сондықтан бір жерде алынған нәтижені басқа аймақтың күліне өзгеріссіз қолдану дұрыс емес. Күлді бетонға қоспас бұрын оның химиялық құрамын, күйдіру кезіндегі масса жоғалуын, ұнтақтылық дәрежесін және кремний диоксидінің күйін анықтау қажет.

2. Күріш қауызының құрамы

Күріш қауызының құрамына ылғал, органикалық заттар, талшықтар, ақуыз және минералдық бөлік кіреді. Органикалық бөлігі негізінен целлюлоза, гемицеллюлоза және лигниннен тұрады. Минералдық бөлікте кремний диоксиді басым. Бастапқы мақалада келтірілген күріш қауызының орташа химиялық құрамы 1-кестеде берілді.

Кесте 1 - Күріш қауызының химиялық құрамы

	Көрсеткіш	Массалық үлесі, %
	Ылғал мөлшері	8,47 -11,00
	Күл	15,68 -18,59
	Шикі ақуыз	2,94 -3,62
	Эфирде еритін экстракт	0,82 -1,20
	Шикі талшық	19,05 -42,90
	SiO ₂	18,17

Кестедегі мәндер күріш қауызының органикалық және минералдық шикізат ретінде бір уақытта қарастырылатынын көрсетеді. Қауызды жағу кезінде органикалық заттар ыдырап, көмірқышқыл газы, су буы және басқа газ тәрізді өнімдер бөлінеді. Минералдық компоненттер күлде қалады. Сол себепті күлдегі SiO₂ мөлшері бастапқы қауыздағы мөлшерден әлдеқайда жоғары болады және сапалы күлде ол негізгі компонентке айналады.

Күл құрамында SiO₂-ден басқа калий, кальций, магний, темір, алюминий және басқа элементтердің оксидтері болуы мүмкін. Олардың мөлшері әдетте кремний диоксидімен салыстырғанда аз болғанымен, күлдің цементпен әрекеттесуіне және сақтау кезіндегі тұрақтылығына ықпал етуі ықтимал. Күлде жанбай қалған көміртек көп болса, оның түсі қараяды және су мен химиялық қоспаларды сіңіруі артады. Бұл бетон қоспасының қажетті қозғалғыштығын алуды қиындатады.

3. Күріш қауызының күлін алу ерекшеліктері

3.1 Жағу температурасының әсері

Күріш қауызының күлінің сапасын анықтайтын негізгі факторлардың бірі - жағу температурасы. Кремний диоксиді аморфты және кристалдық күйде болуы мүмкін. Аморфты күйдегі кремний диоксидінің құрылымы ретсіз болғандықтан, ол цементтің қатаю ортасында белсендірек әрекеттеседі. Кристалдық кремний диоксидінің құрылымы тұрақты және оның реакцияға түсу қабілеті төмен.

Деректерде күріш қауызын шамамен 500 -700 °C аралығында бақыланатын жағдайда жағу белсенді аморфты кремний диоксидіне бай күл алуға мүмкіндік беретіні көрсетілген [3, 4, 9]. Температура тым төмен болып, ауа жеткіліксіз берілсе, органикалық бөлік толық жанбайды. Мұндай күлде көміртек көп қалып, оның сапасы төмендейді. Ал температура 800 -850 °C-тан жоғары көтеріліп, материал ұзақ уақыт қыздырылса, аморфты кремний диоксиді біртіндеп кристалдық күйге ауысуы мүмкін. Сондықтан тек температураны емес, жағу уақытын, ауа мөлшерін және салқындату жылдамдығын да бақылау қажет.

Өнеркәсіп жағдайында күріш қауызы әртүрлі пештерде жағылады. Қарапайым ашық жағу кезінде температура біркелкі болмайды: бір бөлігі толық жанбай қалса, екінші бөлігі артық қызуы мүмкін. Нәтижесінде құрамы мен қасиеті тұрақсыз күл алынады. Қайнаған қабатты немесе ауа берілуі реттелетін пештер температураны бірқалыпты ұстап, сапасы тұрақты күл алуға қолайлы [3]. Зертханалық тәжірибеде бастапқы күріш қауызы термиялық өңдеуге дейін табиғи қоңыр түсті болды (Сурет 1). Қауызды 800 °C температурада шамамен 2 сағат ұстау арқылы термиялық өңдеу жүргізілді. Өңдеу барысында қауыз көмірленген қара түсті күйден ақшыл түсті минералдық қалдыққа дейін өзгерді (Сурет 2).



Сурет 1. Термиялық өңдеуге дейінгі бастапқы күріш қауызы



А



Ә

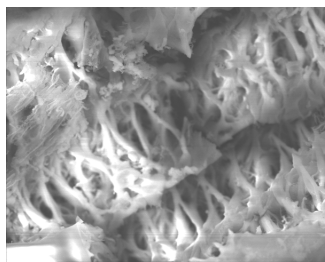
Сурет 2. Күріш қауызының термиялық өңдеуден кейінгі сыртқы көрінісі: а - 800 °С температурада 2 сағат термиялық өңдеуден кейінгі үлгі; ә - термиялық өңдеу барысындағы көмірленген күріш қауызы

3.2 Алдын ала өңдеу және ұнтақтау

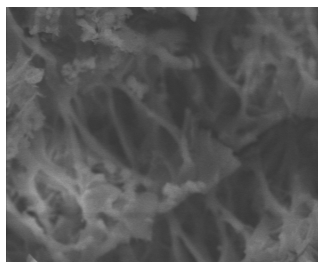
Күріш қауызы шаңнан, топырақтан және басқа қоспалардан тазартылғаннан кейін кептіріледі. Кейбір технологияларда қауызды жағу алдында минералдық қышқылдың әлсіз ерітіндісімен өңдеу ұсынылады. Мұндай өңдеу калий, кальций, темір сияқты қоспалардың бір бөлігін кетіріп, алынатын кремний диоксидінің тазалығын арттыруы мүмкін. Одан кейін қауыз сумен жуылып, кептіріледі және белгіленген температурада жағылады. Қышқылмен өңдеу қосымша су мен реагентті қажет ететіндіктен, оның тиімділігі өнімнің мақсатына қарай бағалануы тиіс.

Жағудан кейінгі күлдің бөлшектері көбіне кеуекті және әркелкі болады. Күлді ұнтақтау ірі бөлшектерді майдалап, цементпен жақсы араласуына жағдай жасайды. Ұсақ бөлшектер цемент түйіршіктерінің арасындағы бос орындарды толтырып, бетон құрылымының тығыздалуына ықпал етеді. Сонымен қатар олардың беті үлкейген сайын кремний диоксидінің реакцияға қатысу мүмкіндігі артады. Бірақ күл шамадан тыс ұсақталса, оның суға қажеттілігі де өсуі мүмкін. Сондықтан ұнтақтау ұзақтығы нақты шикізат үшін тәжірибе арқылы таңдалуы керек.

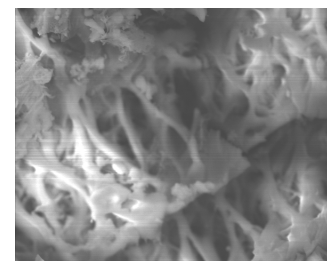
Күлдің сапасын бақылау кезінде оның химиялық құрамы, күйдіру кезіндегі масса жоғалуы, ылғалдылығы, бөлшектерінің өлшемі және меншікті беті анықталады. Рентгендік талдау арқылы кремний диоксидінің аморфты немесе кристалдық күйі бағаланады. Бұл көрсеткіштер бетон құрамын жобалауға және әр партиядағы күлдің қасиеттерін салыстыруға мүмкіндік береді.



а - x950



ә - x1400

б - өңделген кескін,
x1400

Сурет 3. Күріш қауызы күлінің микроқұрылымы

4. Күріш қауызы күлінің цементпен әрекеттесуі

Портландцементке су қосылғанда цемент минералдары гидратацияланады және бетонның беріктігін қалыптастыратын өнімдер пайда болады. Осы процесте кальций гидроксиді де түзіледі. Ол бетонға негізгі беріктік беретін компонент емес және кейбір агрессивті орта әсерінен оңай шайылуы немесе химиялық реакцияға түсуі мүмкін. Күріш қауызының күліндегі белсенді SiO_2 кальций гидроксидімен әрекеттесіп, қосымша кальций гидросиликаттарын түзеді. Бұл процесс пуццоландық реакция деп аталады.

Қосымша түзілген кальций гидросиликаттары цемент тасындағы қуыстарды азайтып, оның құрылымын тығыздайды. Соның нәтижесінде кейінгі мерзімдердегі беріктік артып, судың және агрессивті ерітінділердің бетонға өтуі қиындайды. Бұл реакция бірден аяқталмайды. Алғашқы тәуліктерде беріктіктің қалыптасуына негізінен цементтің өзі қатысады, ал күріш қауызы күлінің әсері 28 тәулік және одан кейін айқынырақ байқалуы мүмкін [10 -13].

Күріш қауызының күлі бетонға тек химиялық жолмен әсер етпейді. Оның майда бөлшектері цемент пен толтырғыш арасындағы бос орындарды толтырады. Бұл физикалық әсер бетонның ішкі құрылымын біркелкі етуге көмектеседі. Сонымен қатар ұсақ бөлшектер цементтің гидратация өнімдері жиналатын қосымша бет ретінде қызмет етеді. Демек, күріш қауызы күлінің әсері үш бағыттан тұрады: бос орындарды толтыру, цементтің қатаюына қолайлы бет құру және кальций гидроксидімен химиялық әрекеттесу.

Күріш қауызы күлінің мөлшері тым көп болса, цемент мөлшері азайып, ерте жастағы беріктік төмендеуі мүмкін. Сонымен бірге кеуекті күл судың бір бөлігін сіңіріп, қоспаның қоюлануына әкеледі. Сондықтан күлдің тиімді мөлшерін таңдау оның химиялық белсенділігімен қатар бетон қоспасының суға қажеттілігіне де байланысты.

5. Бетон қоспасының қасиеттеріне әсері

Күріш қауызының күлін бетон құрамына енгізгенде ең алдымен қоспаның қозғалғыштығы өзгереді. Күл бөлшектерінің беті кеуекті және меншікті беті жоғары болғандықтан, олар суды көбірек ұстайды. Су мөлшері өзгермесе, бетон қоспасы қоюланып, оны араластыру және қалыпқа салу қиындауы мүмкін. Су мөлшерін жай ғана көбейту бетонның кейінгі беріктігін төмендетеді. Сондықтан күріш қауызының күлі қосылған бетонда суды азайтатын химиялық қоспаларды пайдалану орынды.

Суперпластификатор цемент пен күл бөлшектерінің бір-біріне жабысып қалуын азайтып, олардың қоспада біркелкі таралуына көмектеседі. Соның арқасында қосымша су қоспай-ақ қажетті қозғалғыштыққа қол жеткізуге болады. Бірақ суперпластификатордың мөлшері күлдің қасиетіне қарай таңдалуы керек. Жанбай қалған көміртегі көп күл химиялық қоспаның бір бөлігін өз бетіне сіңіріп, оның әсерін төмендетеді.

Қоспаның сапасына компоненттерді араластыру реті де әсер етеді. Алдымен құрғақ материалдарды біркелкі араластырып, содан кейін су мен химиялық қоспаны қосуға болады. Басқа тәсілде күріш қауызының күлі цементпен және суперпластификатор ерітіндісімен алдын ала бірге ұнтақталады немесе араластырылады. Мұндай механикалық белсендіру бөлшектердің таралуын жақсартуға және күлдің тиімділігін арттыруға бағытталған. Дегенмен белсендіру уақыты, диірмен түрі және энергия шығыны нақты көрсетілуі қажет.

6. Бетонның беріктігіне әсері

Күріш қауызы күлінің бетон беріктігіне әсері оның мөлшеріне, ұнтақтылығына, жағу режиміне, цемент түріне және су-цемент қатынасына байланысты. Көптеген зерттеулерде дұрыс дайындалған күріш қауызының күлі цементтің бір бөлігін алмастырғанда 28 және 90 тәуліктегі сығу беріктігінің сақталатыны немесе артатыны көрсетілген [10 -14]. Әдетте тиімді мөлшер орташа шекте болады. Алайда барлық күл үшін бірдей нақты пайыз белгілеу мүмкін емес.

Аз мөлшердегі белсенді күл цемент бөлшектерінің арасын толтырып, кейіннен кальций гидроксидімен әрекеттеседі. Бұл бетонның құрылымын нығайтады. Күл мөлшері шамадан тыс артқанда цемент үлесі азайып, қатаюдың бастапқы кезеңінде жеткілікті байланыстырғыш өнім түзілмеуі мүмкін. Егер қоспаның қозғалғыштығын сақтау үшін су көбейтілсе, артық судан қуыстар пайда болып, беріктік төмендейді.

Беріктікті бағалағанда тек 28 тәуліктегі нәтижемен шектелмеу керек. Күріш қауызы күлінің пуццоландық реакциясы салыстырмалы түрде баяу жүретіндіктен, 56 және 90 тәуліктегі нәтижелер оның әсерін толығырақ көрсетеді. Сонымен бірге салыстырылатын құрамдарда су-байланыстырғыш қатынасы және қоспаның қозғалғыштығы бірдей болуы тиіс. Әйтпесе беріктіктегі айырмашылықты тек күріш қауызы күлінің әсерімен түсіндіру дұрыс болмайды.

7. Бетонның физикалық қасиеттері мен ұзақ мерзімділігі

7.1 Су сіңіргіштік және су өткізбейтіндік

Бетонның су сіңіргіштігі оның ішкі қуыстарының санына және олардың өзара байланысына тәуелді. Белсенді және жақсы ұнтақталған күріш қауызының күлі цемент тасындағы қуыстарды азайтып, судың өту жолдарын қиындатады. Соның нәтижесінде су сіңіргіштік төмендеп, су өткізбейтіндік артуы мүмкін. Бұл әсіресе ылғал, тұз және басқа агрессивті заттар әсер ететін конструкциялар үшін маңызды.

Дегенмен күл сапасыз болып, бетон қоспасын дайындау үшін артық су қолданылса, кері нәтиже болуы мүмкін. Сондықтан су сіңіргіштіктің төмендеуі күріш қауызы күлінің өзіне ғана емес, бүкіл бетон құрамының дұрыс таңдалуына байланысты. Су мөлшері, суперпластификатор дозасы және қоспаны тығыздау сапасы бірге ескерілуі қажет.

7.2 Аязға төзімділік

Аязға төзімділік - бетонның сумен қаныққан күйде бірнеше рет мұздап, ерігеннен кейін беріктігі мен тұтастығын сақтау қабілеті. Су бетон қуыстарында мұзға айналғанда оның көлемі ұлғайып, ішкі қысым пайда болады. Егер бетонның құрылымы бос және су сіңіргіштігі жоғары болса, мұздату мен еріту циклдері жарықтардың түзілуіне әкеледі.

Күріш қауызының күлі бетон құрылымын тығыздап, су сіңіргіштікті төмендеткен жағдайда оның аязға төзімділігі артуы мүмкін. Бірақ мұнда ауа тартқыш қоспалар, толтырғыштардың сапасы, бетонның бастапқы ылғалдылығы және сынақ әдісі де маңызды. Сондықтан аязға төзімділікті арттыру үшін күріш қауызының күлін қолдану жалпы құрамды дұрыс жобалаумен бірге жүргізілуі тиіс.

7.3 Агрессивті ортаға төзімділік

Тығыз құрылымды бетонға хлоридтер мен сульфаттардың енуі баяулайды. Белсенді күріш қауызының күлі кальций гидроксидінің бір бөлігін байланыстыратындықтан, цемент тасының кейбір химиялық әсерлерге тұрақтылығы артуы мүмкін. Зерттеулерде күріш қауызының күлі қосылған бетонның хлорид иондарының өтуіне және сульфат ерітінділерінің әсеріне төзімділігі жақсарғаны көрсетіледі [11 -15]. Бірақ бұл қасиеттер күлдің мөлшеріне, цементтің құрамына және сынақ ортасына байланысты.

Арматураланған бетон үшін көмірқышқыл газының бетонға енуін де ескеру керек. Күріш қауызының күлі құрылымды тығыздағанымен, кальций гидроксидінің мөлшерін азайтады. Сондықтан арматураны қорғау қабілетін бағалағанда тек су сіңіргіштік емес, карбонизация тереңдігі де зерттелуі қажет.

8. Тәжірибелік зерттеу нәтижелері

Бастапқы жұмыста күріш қауызының күлі, портландцемент, құм, қиыршық тас және аз мөлшердегі мұнай шламы қолданылған бетон құрамдары зерттелген. Мұнай шламы бұл жұмыста жеке зерттеу нысаны емес, тәжірибелік құрамның бір компоненті ретінде қарастырылды. Сондықтан алынған беріктік нәтижелері күріш қауызының күлі мен басқа компоненттердің бірлескен әсерін сипаттайды.

Үш құрамда портландцемент мөлшері 18,0-ден 15,0 %-ға дейін төмендетіліп, күріш қауызы күлінің мөлшері 3-тен 5 %-ға дейін және мұнай шламы 0,8-ден 1,2 %-ға дейін арттырылған. 7 және 28 тәуліктегі сығу беріктігінің нәтижелері 2-кестеде берілді.

Кесте 2 - Күріш қауызының күлі қосылған бетонның құрамы және сығу беріктігі

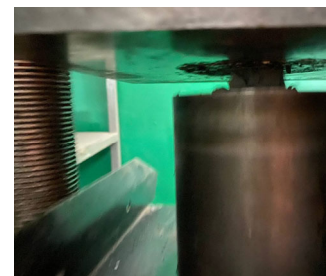
	Портландцемент М400, %	Мұнай шламы, %	Күріш қауызының күлі, %	Құм, %	Қиыршық тас, %	7 тәулік, МПа	28 тәулік, МПа
	18,0	0,8	3	38	30	45,2	68,8
	16,5	0,9	4	38	30	44,7	67,2
	15,0	1,2	5	37	31	43,2	66,4



а



ә



б

Сурет 4. Бетон үлгілерін сығуға сынау: а - дайын текше үлгілер; ә - үлгіні престо орналастыру; б - жүктеме беру барысы



Сурет 5. Бетон үлгісінің сығу жүктемесі әсерінен бұзылу сипаты

Кесте нәтижелері бойынша барлық зерттелген құрамдарда 28 тәуліктегі сығу беріктігі 66,4 -68,8 МПа аралығында болды. Ең жоғары беріктік бірінші құрамда алынды: 7 тәулікте 45,2 МПа және 28 тәулікте 68,8 МПа. Күріш қауызы күлінің мөлшері 3 %-дан 5 %-ға дейін артқан кезде беріктік аздап төмендеген. Сығуға сынау кезінде үлгіге біртіндеп өсетін жүктеме беріліп, жарықшақтардың түзілуі мен таралуы бақыланды. Бұзылу сатысында

үлгінің бетінде бойлық және көлбеу жарықшақтар дамып, шеткі бөліктерінде бетонның үгітілуі байқалды (Сурет 5).

Бұл өзгерісті бір ғана күріш қауызы күлінің мөлшерімен түсіндіруге болмайды, себебі құрамдарда портландцемент, мұнай шламы, құм және қиыршық тас мөлшері де өзгерген. Соған қарамастан нәтижелер цемент мөлшері 15 -18 % аралығында және күріш қауызының күлі 3 - 5 % болған кезде жоғары беріктік алуға болатынын көрсетеді. Алынған деректер келесі зерттеулер үшін тиімді құрамды нақтылауға негіз бола алады.

Нәтижелерді толық дәлелдеу үшін болашақ тәжірибеде күріш қауызының күлі қосылмаған бақылау бетонды, мұнай шламы жоқ, күріш қауызының күлі қосылған құрамды және әр компоненттің мөлшері жеке өзгертілетін құрамдарды салыстыру қажет. Сынақтар кемінде 3, 7, 28, 56 және 90 тәулікте жүргізіліп, сығу беріктігімен қатар су сіңіргіштік, аязға төзімділік және бетон құрылымы анықталғаны дұрыс.

9. Күріш қауызының күлі негізіндегі кешенді органоминалдық қоспалар

Күріш қауызының күлін бетонға жеке минералдық қоспа түрінде ғана емес, цементпен және химиялық қоспамен бірге дайындалатын кешенді қоспа құрамында пайдалануға болады. Мұндай тәсілдің мақсаты - күлдің белсенділігін арттыру, бөлшектерді қоспада біркелкі тарату және артық су қоспай бетонның қажетті қозғалғыштығын қамтамасыз ету.

Кешенді қоспаның минералдық бөлігіне күріш қауызының күлі мен цемент, ал органикалық бөлігіне суперпластификатор кіреді. Бұл компоненттер бірге ұнтақталғанда күл бөлшектері майдаланып, цементпен жанасуы жақсарады. Суперпластификатор бөлшектердің жабысып қалуын азайтады. Нәтижесінде күлдің майда бөлшектері цемент тасындағы бос орындарды толтырып, кейін пуццоландық реакцияға қатысады.

Кешенді қоспаның тиімділігі оның барлық компоненттері дұрыс таңдалғанда ғана байқалады. Күлдің сапасы төмен болса немесе оның мөлшері шамадан тыс артса, суперпластификатор шығыны көбейіп, қоспаның қозғалғыштығы төмендеуі мүмкін. Сондықтан күріш қауызының күлі, цемент, су және химиялық қоспа мөлшерін бір-бірінен бөлек емес, бір жүйе ретінде қарастыру қажет. Әрбір жаңа күл партиясы үшін бақылау сынақтары жүргізілгені жөн.

10. Экологиялық және экономикалық маңызы

Күріш қауызының күлін бетон өндірісінде пайдалану екі міндетті қатар шешуге мүмкіндік береді. Біріншіден, ауыл шаруашылығы қалдығы пайдалы өнімге айналады және оны сақтау немесе көму қажеттілігі азаяды. Екіншіден, цементтің бір бөлігін күлмен алмастыру арқылы цемент шығынын төмендетуге болады. Бұл цемент өндірісіне қажет табиғи шикізат пен энергияны үнемдеуге ықпал етеді.

Алайда күріш қауызының күлін қолданудың тиімділігін бағалағанда оны дайындауға жұмсалатын энергия мен шығынды да есептеу қажет. Қауызды тасымалдау, кептіру, бақыланатын жағдайда жағу, күлді ұнтақтау және сапасын тексеру қосымша операциялар болып табылады. Егер бұл жұмыстар күріш өңдеу кәсіпорнына және бетон зауытына жақын жерде ұйымдастырылса, тасымалдау шығыны азайып, технологияның экономикалық тиімділігі жоғарылайды.

Қызылорда облысында күріш өндірісі мен құрылыс материалдары өндірісін байланыстыратын жергілікті жүйе құруға мүмкіндік бар. Күріш өңдеу кәсіпорындарынан алынған қауызды бақыланатын пеште жағу, күлді сұрыптау және ұнтақтау арқылы бетон зауыттарына тұрақты сападағы минералдық қоспа жеткізуге болады. Бұл үшін күріш қауызы күлінің сапасына қойылатын талаптар мен қабылдау сынақтары әзірленуі тиіс.

11. Күріш қауызының күлін қолдануда ескерілетін негізгі талаптар

Күріш қауызының күлін бетон өндірісінде тұрақты қолдану үшін бірнеше талап сақталуы қажет. Бірінші талап - қауызды жағу температурасы мен уақытын бақылау. Екінші талап - күлдегі жанбай қалған көміртек пен зиянды қоспалардың мөлшерін анықтау. Үшінші талап - күлді қажетті дәрежеге дейін ұнтақтау және оның бөлшектерінің тұрақты құрамын қамтамасыз ету. Төртінші талап - бетонның суға қажеттілігін ескеріп, суперпластификатор мөлшерін тәжірибе арқылы таңдау.

Күріш қауызы күлінің мөлшерін тек басқа зерттеулердегі пайызға сүйеніп қабылдауға болмайды. Алдымен зерттелетін күлдің қасиеттері анықталып, содан кейін бірнеше сынақ құрамы дайындалуы тиіс. Құрамдарды салыстырғанда олардың су-байланыстырғыш қатынасы, қозғалғыштығы және қатаю жағдайлары бірдей болуы қажет. Сонда ғана беріктіктегі немесе су сіңіргіштіктегі өзгерістің күріш қауызының күліне байланысты екенін дұрыс бағалауға болады.

Өндірістік жағдайда күріш қауызы күлінің әр партиясына қысқаша сапа құжаты жасалғаны жөн. Онда күлдің алынған орны, жағу температурасы, ылғалдылығы, химиялық құрамы, ұнтақтылығы және сынақ нәтижелері көрсетілуі тиіс. Мұндай бақылау бетон қасиеттерінің тұрақтылығын қамтамасыз етеді.

Қорытынды

Күріш қауызының күлі - кремний диоксидіне бай және бетон өндірісінде белсенді минералдық қоспа ретінде қолдануға болатын ауыл шаруашылығы қалдығы. Оның тиімділігі ең алдымен қауызды жағу режиміне байланысты. Шамамен 500 -700 °C аралығында бақыланатын жағу аморфты кремний диоксиді басым күл алуға мүмкіндік береді, ал тым жоғары температура оның кристалдық күйге ауысуына әкелуі мүмкін.

Күріш қауызының күлі бетонға физикалық және химиялық жолмен әсер етеді. Ұнтақталған күл бөлшектері цемент пен толтырғыш арасындағы бос орындарды толтырады, ал белсенді кремний диоксиді цемент гидратациясы кезінде түзілген кальций гидроксидімен әрекеттеседі. Соның нәтижесінде бетон құрылымы тығыздалып, кейінгі мерзімдердегі беріктігі, су өткізбейтіндігі және аязға төзімділігі жақсаруы мүмкін.

Сонымен бірге күріш қауызы күлінің кеуекті құрылымы бетон қоспасының суға қажеттілігін арттырады. Сондықтан оны қолданғанда су мөлшерін негізсіз көбейтпей, тиімді суперпластификатор пайдалану және қоспаның қозғалғыштығын бақылау қажет. Күлдің тиімді мөлшері оның сапасына және бетонның толық құрамына байланысты тәжірибе арқылы анықталады.

Жүргізілген тәжірибеде күріш қауызы күлінің мөлшері 3 -5 %, мұнай шламы 0,8 -1,2 % және портландцемент 15 -18 % болған құрамдарда 28 тәуліктегі сығу беріктігі 66,4 -68,8 МПа аралығында болды. Ең жоғары нәтиже күріш қауызының күлі 3 % болған бірінші құрамда алынды. Бірақ құрамдағы бірнеше компонент қатар өзгергендіктен, бұл көрсеткіштер олардың бірлескен әсерін сипаттайды.

Жалпы алғанда, күріш қауызының күлін дұрыс дайындау, ұнтақтау және бетонның басқа компоненттерімен үйлестіру күріш өндірісінің қалдығын тиімді пайдалануға, цемент шығынын азайтуға және жоғары сапалы бетон алуға мүмкіндік береді. Келесі зерттеулерде күріш қауызы күлінің жеке әсерін анықтайтын бақылау құрамдарын енгізіп, бетонның ұзақ мерзімді беріктігі мен төзімділігін кешенді бағалау қажет.

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Political Studies

France's Investments in Kazakhstan as an Instrument of Economic Diplomacy

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Abstract

This article examines the role of French investments in Kazakhstan as a strategic instrument of economic diplomacy. Amid shifting geopolitical landscapes and growing competition for Central Asian markets, economic engagement has evolved beyond pure commercial interest into a vital tool for bilateral relations. Utilizing a qualitative and empirical approach, the study analyzes major French corporate footprints in Kazakhstan – particularly in energy, infrastructure, and mining – and evaluates their impact on diplomatic ties and regional stability. The findings indicate that France's economic strategy in Kazakhstan serves not only mutual commercial benefits but also strengthens Paris's geopolitical positioning in Central Asia.

This scientific article examines the strategic role of European Union investments in Kazakhstan as a vital instrument of modern economic diplomacy. Amid shifting global geopolitical landscapes and evolving trade corridors, the European Union remains one of the largest foreign investors in the Central Asian region. The study analyzes the bilateral economic frameworks, including the Enhanced Partnership and Cooperation Agreement, to understand how foreign direct investment transcends traditional commercial interests to foster deeper diplomatic alignment, institutional reform, and regional stability. Special attention is devoted to the diversification of Kazakhstan's economy away from hydrocarbon dependency, focusing on EU-backed initiatives in critical raw materials, renewable energy, sustainable infrastructure, and digitalization.

Utilizing a mixed-methods approach that combines quantitative trade-flow analysis with qualitative policy evaluation, the research assesses the mutual benefits and challenges inherent in these economic partnerships. The findings highlight that European investments serve not only as capital injections but as soft-power mechanisms that facilitate regulatory harmonization, enhance governance standards, and strengthen Kazakhstan's multi-vector foreign policy.

Ultimately, the paper concludes that economic diplomacy driven by targeted France investments creates a resilient framework for long-term geopolitical cooperation, balancing European resource security needs with Kazakhstan's modernization objectives.

Keywords: Economic diplomacy, European Union, foreign direct investment, Kazakhstan, Central Asia, sustainable energy, critical raw materials, bilateral relations

Аңдатпа

Бұл мақалада француз инвестицияларының Қазақстандағы рөлі экономикалық дипломатияның стратегиялық құралы ретінде қарастырылады. Өзгеріп жатқан геополитикалық жағдайлар мен Орталық Азия нарықтары үшін күшейіп келе жатқан бәсекелестік жағдайында экономикалық ынтымақтастық тек коммерциялық мүдделер шеңберінен шығып, екіжақты қатынастардың маңызды құралына айналды. Зерттеуде сапалық және эмпирикалық тәсілдер қолданыла отырып, ірі француз корпорацияларының Қазақстандағы қызметі (әсіресе энергетика, инфрақұрылым және тау-кен өнеркәсібі салаларында) талданады және олардың дипломатикалық байланыстар мен өңірлік тұрақтылыққа әсері бағаланады. Зерттеу нәтижелері Францияның Қазақстандағы экономикалық стратегиясы өзара коммерциялық пайда әкеліп қана қоймай, Париждың Орталық Азиядағы геополитикалық ұстанымын нығайта түсетінін көрсетеді.

Бұл ғылыми мақала Еуропалық одақтың Қазақстандағы инвестицияларының заманауи экономикалық дипломатияның маңызды құралы ретіндегі стратегиялық рөлін қарастырады. Жаһандық геосаяси жағдайдың өзгеруі мен сауда дәліздерінің дамуы жағдайында Еуропалық одақ Орталық Азия өңіріндегі ең ірі шетелдік инвесторлардың бірі болып қала береді. Зерттеу тікелей шетелдік инвестициялардың дәстүрлі коммерциялық мүдделерден шыға отырып, қалайша тереңірек дипломатиялық үндестікке, институционалдық реформаларға және өңірлік тұрақтылыққа ықпал ететінін түсіну үшін Кеңейтілген әріптестік пен ынтымақтастық туралы келісімді қоса алғанда, екіжақты экономикалық негіздерді талдайды. Мақалада шикізатқа тәуелділіктен арылу мақсатында Қазақстан экономикасын әртараптандыруға ерекше назар аударылып, сыни маңызы бар шикізат, жаңартылатын энергия көздері, тұрақты инфрақұрылым және цифрландыру салаларындағы ЕО қолдайтын бастамалар қарастырылады.

Сандық сауда ағындарын талдауды сапалық саяси бағалаумен біріктіретін аралас әдістемелік тәсілді қолдана отырып, зерттеу осы экономикалық әріптестіктерге тән өзара тиімді тұстар мен қиындықтарды бағалайды. Нәтижелер еуропалық инвестициялар тек капитал салу құралы ғана емес, сонымен қатар реттеуді үйлестіруге, басқару стандарттарын жақсартуға және Қазақстанның көпвекторлы сыртқы саясатын нығайтуға ықпал ететін «жұмсақ күш» механизмдері ретінде қызмет ететінін көрсетеді.

Түптеп келгенде, мақала мақсатты Францияның инвестициялары арқылы жүзеге асырылатын экономикалық дипломатия еуропалық ресурстық қауіпсіздік қажеттіліктері мен Қазақстанның жаңғырту мақсаттарын үйлестіре отырып, ұзақ мерзімді геосаяси ынтымақтастық үшін тұрақты негіз қалыптастырады деген қорытындыға келеді.

Кілт сөздер: Экономикалық дипломатия, Еуропалық одақ, тікелей шетелдік инвестициялар, Қазақстан, Орталық Азия, тұрақты энергетика, маңызы бар шикізат, екіжақты қатынастар

Аннотация

В данной статье рассматривается роль французских инвестиций в Казахстане как стратегического инструмента экономической дипломатии. На фоне меняющегося геополитического ландшафта и растущей конкуренции за рынки Центральной Азии экономическое взаимодействие переросло рамки чисто коммерческих интересов, превратившись в жизненно важный инструмент двусторонних отношений. Используя качественный и эмпирический подход, исследование анализирует присутствие крупных французских корпораций в Казахстане (в частности, в сферах энергетики, инфраструктуры и

горнодобывающей промышленности) и оценивает их влияние на дипломатические связи и региональную стабильность. Полученные результаты показывают, что экономическая стратегия Франции в Казахстане служит не только взаимной коммерческой выгоде, но и укрепляет геополитические позиции Парижа в Центральной Азии.

В данной научной статье рассматривается стратегическая роль инвестиций Европейского союза в Казахстане как важнейшего инструмента современной экономической дипломатии. На фоне меняющегося глобального геополитического ландшафта и развития торговых коридоров Европейский союз остается одним из крупнейших иностранных инвесторов в Центральноазиатском регионе. В исследовании анализируются двусторонние экономические рамки, включая Соглашение о расширенном партнерстве и сотрудничестве, чтобы понять, как прямые иностранные инвестиции выходят за рамки традиционных коммерческих интересов, способствуя более глубокому дипломатическому сближению, институциональным реформам и региональной стабильности. Особое внимание уделяется диверсификации экономики Казахстана с целью ухода от углеводородной зависимости, при этом основное внимание уделяется поддерживаемым ЕС инициативам в сфере критически важного сырья, возобновляемых источников энергии, устойчивой инфраструктуры и цифровизации.

Используя смешанный методологический подход, сочетающий анализ количественных торговых потоков с качественной оценкой политики, исследование оценивает взаимные выгоды и проблемы, присущие данным экономическим партнерствам. Полученные результаты показывают, что европейские инвестиции служат не только вливанием капитала, но и механизмами «мягкой силы», которые способствуют гармонизации регулирования, повышению стандартов управления и укреплению многовекторной внешней политики Казахстана.

В заключение автор приходит к выводу, что экономическая дипломатия, движимая целевыми инвестициями Франции, создает устойчивую основу для долгосрочного геополитического сотрудничества, балансируя потребности Европы в ресурсной безопасности с целями модернизации Казахстана.

Ключевые слова: Экономическая дипломатия, Европейский союз, прямые иностранные инвестиции, Казахстан, Центральная Азия, устойчивая энергетика, критически важное сырье, двусторонние отношения

Introduction. In the contemporary architecture of international relations, the nexus between economics and diplomacy has undergone a profound transformation, positioning economic diplomacy as a core instrument of statecraft and regional integration. Within this shifting paradigm, the strategic deployment of foreign direct investment (FDI) transcends mere commercial enterprise, operating instead as a sophisticated vector for geopolitical alignment, institutional modernization, and long-term partnership. Kazakhstan, as the geopolitical anchor and economic powerhouse of Central Asia, has increasingly become a focal point for external actors seeking to secure strategic economic corridors and resource partnerships. Among these global players, the European Union (EU) stands out as a preeminent institutional and economic partner. Consequently, investigating EU Investments in Kazakhstan as an Instrument of Economic Diplomacy offers a vital analytical lens through which to observe how transnational capital flows shape bilateral statecraft, regulatory convergence, and regional stability in Eurasia.

The urgency of examining EU investments in Kazakhstan is underscored by a turbulent global landscape characterized by fractured supply chains, intensifying geopolitical competition, and an accelerated global green transition. As Kazakhstan endeavors to pivot away from a traditional hydrocarbon-centric economic model toward a diversified, knowledge-based, and sustainable economy, European capital, technology, and governance standards provide an

indispensable catalyst [1]. The formalization of the Enhanced Partnership and Cooperation Agreement (EPCA) between Kazakhstan and the EU has established a comprehensive legal architecture for deeper integration. However, the practical operationalization of this framework through targeted investments in critical raw materials, renewable energy, sustainable transport infrastructure, and digital ecosystems remains underexplored in contemporary scholarship [2]. Furthermore, understanding how these economic commitments function as instruments of soft power and institutional reform is crucial for navigating the delicate balance of Kazakhstan's multi-vector foreign policy amidst the competing interests of global superpowers.

The primary objective of this research is to comprehensively analyze how European Union investments operate as an instrument of economic diplomacy in Kazakhstan, evaluating both the developmental outcomes for the Central Asian state and the strategic gains for the European bloc. To fulfill this overarching goal, the study sets forth the following key tasks:

1. To evaluate the legal, institutional, and policy frameworks – specifically the EPCA – that govern EU-Kazakhstan economic relations and facilitate bilateral investment flows.
2. To examine the sectoral allocation of European investments, with a distinct focus on initiatives addressing critical raw materials, green energy transition, and sustainable infrastructure development.
3. To assess the role of economic diplomacy and European investments as soft-power mechanisms driving regulatory harmonization, corporate governance standards, and institutional reforms within Kazakhstan.
4. To analyze the bilateral dynamics between Kazakhstan and key European member states, most notably France, to demonstrate how national-level diplomatic and industrial strategies reinforce overarching EU-level objectives.
5. To identify the primary systemic challenges, geopolitical friction points, and mutual benefits inherent in these economic partnerships, culminating in strategic recommendations for future cooperation.

The scientific significance of this research lies in its contribution to the theoretical discourse surrounding economic diplomacy, bridging the conceptual gap between traditional international political economy and modern institutional integration [3]. By treating FDI not merely as a quantitative economic variable, but as a qualitative diplomatic tool, the study provides a nuanced framework for understanding contemporary Eurasian geopolitics. Practically, the findings offer actionable insights for policymakers, corporate strategists, and diplomatic corps in both Astana and Brussels. The insights derived from this study can assist in optimizing future investment agreements, enhancing risk-mitigation strategies in critical supply chains, and refining policy measures aimed at fostering sustainable economic modernization in developing and transition economies.

The Strategic Dimension of France-Kazakhstan Relations. A critical micro-level manifestation of this broader European economic diplomacy is found in the deepening bilateral partnership between Kazakhstan and France. As one of the principal political and industrial heavyweights within the European Union, France has consistently utilized targeted economic diplomacy to cement its presence in Kazakhstan's strategic sectors, particularly in civil nuclear energy, aerospace, rare earth elements, and infrastructure [4]. High-level state visits and strategic intergovernmental agreements have positioned French multinational corporations as key partners in Kazakhstan's green transition and industrial diversification. This bilateral axis exemplifies how national strategic priorities of individual EU member states can synergize with overarching European integration policies. France's engagement in Kazakhstan goes beyond commercial trade; it operates as an active diplomatic instrument that reinforces European technological footprint, secures critical resource supply chains, and fortifies Kazakhstan's multi-vector foreign policy by diversifying its network of high-level Western partnerships. Ultimately, analyzing the Franco-

Kazakh dynamic within the broader context of EU investments illuminates the complex mechanics of how collective economic diplomacy is enacted through bilateral statecraft [5].

Research and Analytical Framework: EU-Kazakhstan and Franco-Kazakh Economic Diplomacy. The economic architecture between Kazakhstan and the European Union represents one of the most robust transnational partnerships in Central Asia, anchored heavily by foreign direct investment (FDI) and bilateral commerce. The European Union historically maintains its position as Kazakhstan’s largest foreign investor and primary trading partner, accounting for roughly half of total accumulated foreign investment inflow into the country since independence. This economic relationship is institutionalized through the Enhanced Partnership and Cooperation Agreement (EPCA), which provides a stable legal framework for trade, regulatory approximation, and sustainable sector development [6].

Kazakhstan's export profile to the EU remains dominated by energy resources, specifically crude oil and natural gas, which serve vital energy security needs for European member states. Conversely, EU exports to Kazakhstan heavily feature machinery, advanced technological equipment, pharmaceuticals, and transport vehicles. However, both actors are actively shifting their economic focus toward high-value sectors, including green energy transition, critical raw materials (CRMs), and digital infrastructure, steering away from pure resource extraction toward diversified, technology-driven industrial cooperation (figure – 1).

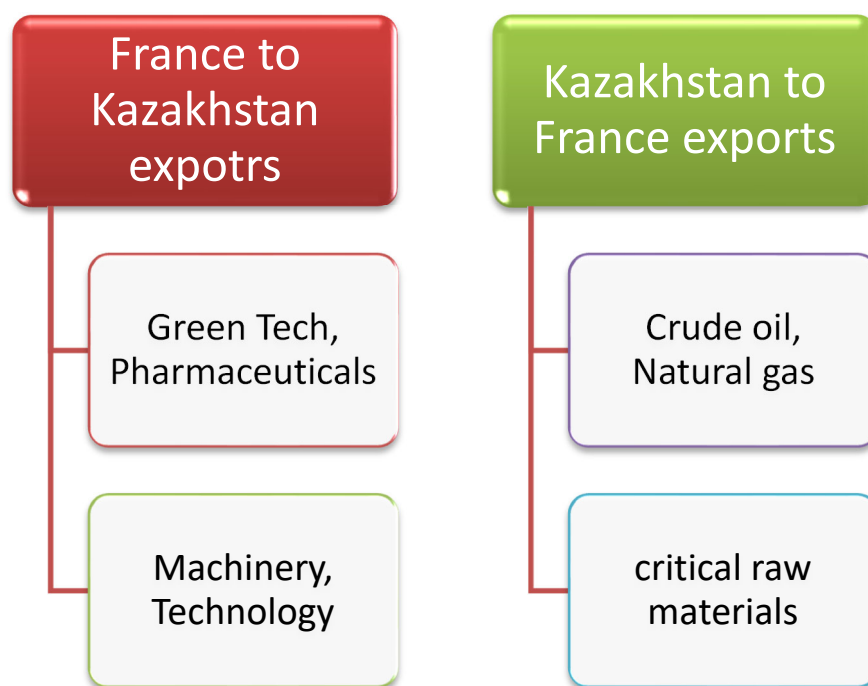


Figure – 1. Structural composition of EU-Kazakhstan Bilateral and Investment

Strategic Franco-Kazakh Economic and Diplomatic Relations. Within the broader framework of EU economic diplomacy, France plays a distinct, leading role as a key political and industrial partner for Kazakhstan. Bilateral relations between Astana and Paris have evolved into a strategic alliance characterized by high-level political dialogues and major industrial joint ventures. French multinational corporations—such as TotalEnergies, Orano, Alstom, and Airbus maintain a deep-seated operational footprint in Kazakhstan across sectors ranging from civil nuclear energy and uranium mining to aerospace, railway logistics, and renewable power generation [7].

France’s economic diplomacy in Kazakhstan functions as a direct extension of its national energy security and industrial sovereignty strategies, aligning seamlessly with the European

Union's broader quest for supply chain diversification. For Kazakhstan, the influx of French capital and proprietary technology acts as a vital counterbalance in its multi-vector foreign policy, reducing over-reliance on any single Eastern or Western power. Joint projects in wind and solar energy, alongside civil nuclear cooperation protocols, underscore how French industrial engagement directly contributes to Kazakhstan's low-carbon modernization and sustainable development goals (figure – 2).

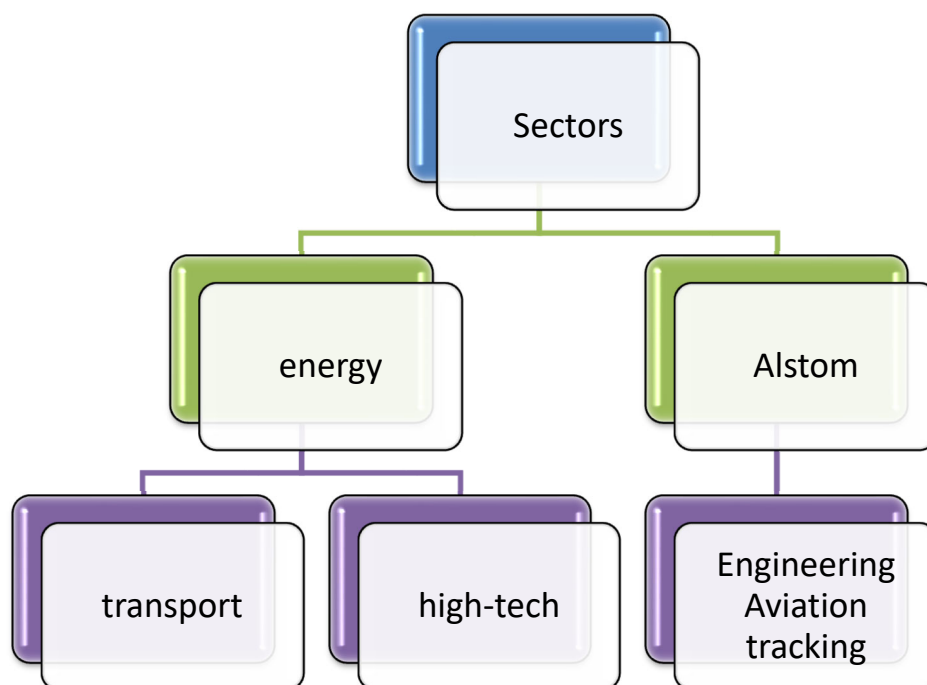


Figure – 2. Key Sectors of Franco-Kazakh Industrial and Economic Cooperation

Geopolitical Alignment and Sustainable Development. Economic diplomacy between European entities and Kazakhstan operates within an increasingly complex geopolitical environment. Situated at the crossroads of Eurasia, Kazakhstan utilizes its economic partnerships with Western actors to navigate regional pressures and enhance its sovereign agency. European investments serve as instruments of "soft power" that introduce high standards of corporate governance, transparency, environmental compliance, and regulatory harmonization into the Kazakh market [8].

Furthermore, the emphasis on sustainable development has become a cornerstone of bilateral agendas. As global supply chains realign around the Trans-Caspian International Transport Route (the Middle Corridor), European investments in Kazakh logistics, digital connectivity, and green infrastructure play a pivotal role. This convergence of interests ensures that economic diplomacy is not merely a tool for commercial profit, but a stabilizing mechanism that fosters regional resilience, environmental modernization, and long-term geopolitical equilibrium in Central Asia [9].

Conclusion. The comprehensive analysis of French investments in Kazakhstan reveals a profound evolution in modern economic diplomacy, where traditional commercial transactions serve as foundational vehicles for deeper geopolitical, institutional, and structural alignment. By acting as a leading foreign investor and a crucial European partner in Kazakhstan, France transcends simple resource acquisition, deploying capital as a sophisticated instrument of soft power and strategic convergence. The robust diplomatic and economic framework between the two nations has successfully operationalized mutual resilience, bridging French strategic industrial demands with Kazakhstan's imperative for national modernization.

At the micro-level, the bilateral partnership between Kazakhstan and France exemplifies how national-level industrial statecraft can drive effective long-term cooperation. French multinational engagement across critical sectors—such as civil nuclear energy, uranium mining, renewable power, and railway logistics—demonstrates that economic diplomacy functions best when anchored in high-value, high-tech collaboration. These strategic ventures not only secure French supply chains for critical raw materials and green technology components, but also actively support Kazakhstan's broader transition toward a diversified, sustainable, and knowledge-based economy.

Furthermore, these economic engagements play a vital role in reinforcing Kazakhstan's multi-vector foreign policy. By deepening its partnership with France as a key European actor, Astana successfully navigates complex regional pressures and bolsters its sovereign agency amidst shifting global power dynamics. French capital inflows concurrently introduce rigorous standards of corporate governance, environmental compliance, and transparency, fostering institutional reforms that resonate deeply throughout the domestic economic ecosystem.

Looking ahead, the convergence of French-Kazakhstan interests along strategic trade vectors, most notably the Trans-Caspian International Transport Route, highlights the enduring relevance of bilateral economic diplomacy as a stabilizing force in Eurasia. Future cooperation will increasingly hinge upon the successful execution of green energy initiatives, digitalization projects, and resilient supply chain integration. Ultimately, the sustained synergy between French investment strategies and Kazakhstan's development objectives establishes a durable blueprint for long-term geopolitical cooperation, proving that economic diplomacy remains an indispensable catalyst for mutual prosperity and regional stability in the twenty-first century.

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The Role of Italy in Infrastructure Development in Kazakhstan

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Abstract

This study examines the pivotal role of Italy in Kazakhstan's infrastructure development, focusing on the strategic economic and industrial partnerships established between the two nations. Over recent decades, Italian engineering, construction, and energy giants have significantly contributed to modernizing Kazakhstan's transport networks, energy grids, and urban infrastructure, moving beyond traditional hydrocarbon cooperation into high-value engineering sectors.

Utilizing a qualitative and empirical methodology, the research analyzes major bilateral projects – particularly in civil works, logistics corridors, and sustainable energy infrastructure to evaluate their impact on Kazakhstan's national modernization and economic diversification. The findings indicate that Italian corporate engagement serves as a vital catalyst for regional connectivity and technological transfer.

Furthermore, this cooperation reinforces Kazakhstan's multi-vector foreign policy and enhances Italy's geopolitical and economic footprint in Central Asia. Ultimately, the partnership demonstrates how targeted foreign investment and collaborative engineering foster mutual economic resilience and long-term stability in the Eurasian region.

Keywords: Italy, Kazakhstan, Infrastructure Development, Foreign Investment, Economic Cooperation, Energy Projects, Central Asia, Transport Networks.

Аңдатпа

Бұл зерттеу Италияның Қазақстанның инфрақұрылымын дамытудағы шешуші рөлін қарастырып, екі ел арасында орнатылған стратегиялық экономикалық және өнеркәсіптік серіктестіктерге баса назар аударады. Соңғы онжылдықтарда итальяндық инженерлік, құрылыс және энергетика алпауыттары дәстүрлі көмірсутекті ынтымақтастық шеңберінен шығып, Қазақстанның көлік желілерін, энергетикалық жүйелерін және қалалық инфрақұрылымын жаңғыртуға елеулі үлес қосты.

Зерттеу сапалық және эмпирикалық әдіснаманы қолдана отырып, Қазақстанның ұлттық жаңғыруы мен экономикалық әртараптандыруына әсерін бағалау үшін негізгі екіжақты жобаларды – әсіресе азаматтық құрылыс, логистикалық дәліздер және тұрақты энергетика инфрақұрылымы салаларындағы жобаларды талдайды. Нәтижелер итальяндық корпорациялардың қатысуы өңірлік байланыс пен технологиялық трансфер үшін маңызды катализатор қызметін атқаратынын көрсетеді.

Сонымен қатар, бұл ынтымақтастық Қазақстанның көпвекторлы сыртқы саясатын нығайтып, Италияның Орталық Азиядағы геополитикалық және экономикалық ықпалын арттырады. Нәтижесінде серіктестік мақсатты шетелдік инвестициялар мен бірлескен

инженерия Еуразия аймағында өзара экономикалық тұрақтылық пен ұзақ мерзімді тыныштықты қалай қалыптастыратынын көрсетеді.

Кілт сөздер: Италия, Қазақстан, инфрақұрылымды дамыту, шетелдік инвестициялар, экономикалық ынтымақтастық, энергетикалық жобалар, Орталық Азия, көлік желілері.

Аннотация

В данном исследовании рассматривается ключевая роль Италии в развитии инфраструктуры Казахстана с акцентом на стратегическое экономическое и промышленное партнерство между двумя государствами. За последние десятилетия итальянские инженерные, строительные и энергетические гиганты внесли значительный вклад в модернизацию транспортных сетей, энергетических систем и городской инфраструктуры Казахстана, выйдя за рамки традиционного сотрудничества в углеводородном секторе.

Используя качественную и эмпирическую методологию, исследование анализирует основные двусторонние проекты – в частности, в области гражданского строительства, логистических коридоров и устойчивой энергетической инфраструктуры – для оценки их влияния на национальную модернизацию и экономическую диверсификацию Казахстана. Полученные результаты показывают, что участие итальянских корпораций служит важнейшим катализатором региональной взаимосвязи и технологического трансфера.

Кроме того, данное сотрудничество укрепляет многовекторную внешнюю политику Казахстана и усиливает геополитическое и экономическое присутствие Италии в Центральной Азии. В конечном итоге партнерство демонстрирует, как целенаправленные иностранные инвестиции и совместные инженерные разработки способствуют взаимной экономической устойчивости и долгосрочной стабильности в Евразийском регионе.

Ключевые слова: Италия, Казахстан, развитие инфраструктуры, иностранные инвестиции, экономическое сотрудничество, энергетические проекты, Центральная Азия, транспортные сети.

Introduction.

In the contemporary architecture of international relations, physical, digital, and energy connectivity has emerged as the principal currency of geopolitical influence and geo-economic statecraft. As global supply chains face unprecedented vulnerabilities and traditional trade corridors undergo radical realignments, the infrastructure linking continents has transformed into a critical strategic arena. Within this shifting paradigm, Central Asia – and Kazakhstan in particular – occupies a pivotal geographical position, serving as the essential landbridge connecting Europe and Asia. Amidst these sweeping structural changes, the European Union (EU) has significantly amplified its strategic engagement through ambitious connectivity frameworks such as the Global Gateway strategy. Consequently, investigating The Role of the EU in Infrastructure Development in Kazakhstan provides an indispensable analytical lens through which to examine how transnational capital, engineering prowess, and diplomatic intent converge to reshape Eurasian trade routes, foster regional integration, and redefine bilateral partnerships [1].

Relevance and Urgency of the Research. The urgency of examining European Union-backed infrastructure development in Kazakhstan is underscored by a rapidly transforming global trade environment. With northern trade routes constrained by geopolitical friction, the Trans-Caspian International Transport Route – commonly known as the Middle Corridor – has risen to unprecedented strategic prominence. Kazakhstan stands as the core territorial anchor of this corridor, making its infrastructural capacity a decisive factor for Eurasian commercial resilience. However, persistent logistical bottlenecks, inadequate port facilities on the Caspian Sea, and

modernization gaps in rail and digital networks present substantial hurdles to sustained economic growth. European investments, technical expertise, and institutional standards offer an essential counterweight to these challenges, providing the capital and regulatory frameworks necessary to construct sustainable, high-standard transport and energy networks. Furthermore, understanding how these infrastructure initiatives align with Kazakhstan's multi-vector foreign policy and its domestic economic modernization goals is critically important for navigating the complex interplay of intersecting global powers in Central Asia [2].

Research Objectives and Tasks. The primary objective of this research is to comprehensively analyze the scope, mechanisms, and strategic implications of European Union involvement in Kazakhstan's infrastructure development, evaluating both the physical transformation of regional logistics and the broader geopolitical outcomes. To accomplish this overarching goal, the study sets forth the following key tasks:

1. To evaluate the strategic frameworks, financial mechanisms, and policy doctrines – specifically the EU Global Gateway initiative and the Enhanced Partnership and Cooperation Agreement that govern European infrastructure financing in Kazakhstan;
2. To examine the sectoral allocation of European-backed projects, focusing intensely on transport modernization, the Trans-Caspian International Transport Route (Middle Corridor), digital connectivity, and green energy grids;
3. To assess the role of European infrastructure investments as catalysts for regulatory harmonization, environmental compliance, and the institutional adoption of European transport and technical standards within Kazakhstan;
4. To analyze the specific bilateral and industrial contributions of key European member states, most notably Italy, in executing major infrastructural, energy, and industrial engineering projects within Kazakhstan;
5. To identify the primary systemic challenges, geopolitical risks, and mutual benefits inherent in these infrastructure partnerships, culminating in strategic recommendations for optimizing future Eurasian connectivity [3].

Scientific and Practical Significance. The scientific significance of this research lies in its contribution to the theoretical framework of geo-economics and international infrastructure politics, bridging the conceptual gap between transport geography and modern institutional diplomacy. By treating infrastructure not merely as a collection of physical assets, but as a strategic instrument of long-term diplomatic alignment and economic resilience, the study offers a robust model for understanding contemporary Eurasian dynamics [4]. From a practical standpoint, the findings provide actionable insights for policymakers, multilateral development banks, corporate logistics strategists, and diplomatic missions in both Astana and Brussels. The insights generated can assist in streamlining future project financing, enhancing risk-mitigation protocols along cross-border supply chains, and refining policy measures designed to support sustainable economic modernization in landlocked transition economies [5].

The Strategic Dimension of Italy-Kazakhstan Infrastructural and Industrial Cooperation. A vital micro-level pillar of this broader European infrastructural engagement is manifested in the deepening bilateral partnership between Kazakhstan and Italy. As one of the foundational economies within the European Union and Kazakhstan's leading trade partner within the bloc, Italy has consistently utilized targeted economic diplomacy, advanced engineering capabilities, and high-level diplomatic dialogue to secure a prominent role in Kazakhstan's infrastructure and energy sectors. Italian multinational corporations -such as Eni in large-scale energy infrastructure and renewable power development, as well as prominent industrial engineering firms – maintain a robust operational footprint that directly supports Kazakhstan's infrastructural modernization and green transition. High-level state visits and intergovernmental strategic agreements between Astana and Rome have institutionalized this cooperation, ensuring that Italian industrial expertise

feeds directly into the larger EU-led connectivity architecture. Italy's involvement in Kazakhstan's transport, energy grids, and industrial logistics networks goes far beyond simple commercial contracting; it functions as a strategic diplomatic instrument that reinforces the European technological footprint, diversifies Kazakhstan's network of advanced Western partners, and fortifies the country's sovereign multi-vector foreign policy. Ultimately, analyzing the Italian-Kazakh infrastructural dynamic within the overarching framework of EU-Kazakhstan relations elucidates the intricate mechanics of how collective European connectivity objectives are successfully translated into concrete, bilateral industrial achievements [6].

Review.

The strategic partnership between Kazakhstan and the European Union relies heavily on robust infrastructural and commercial integration. The European Union remains a preeminent investor and trade partner for Central Asia, directing substantial capital into modernizing regional connectivity frameworks. Central to this integration is the transformation of the Trans-Caspian International Transport Route (the Middle Corridor), which serves as a vital artery connecting European markets with Asian supply chains.

Kazakhstan's export profile to the EU heavily features primary energy commodities, while European exports center on advanced machinery, transport technology, electrical equipment, and infrastructure construction goods. However, the overarching economic agenda has transitioned from raw resource extraction to comprehensive infrastructural modernization. Through initiatives like the EU Global Gateway, European capital is actively channeled into upgrading port facilities, expanding digital fiber-optic networks across the Caspian Sea, enhancing rail transit efficiency, and deploying smart green energy grids. This structural shift ensures that capital inflows drive long-term institutional resilience and sustainable economic diversification [7].

Strategic Italy-Kazakhstan Economic, Industrial, and Infrastructure Relations. Within the broader framework of EU infrastructure diplomacy, Italy occupies a uniquely prominent position as Kazakhstan's top trading partner within the European Union. Economic relations between Astana and Rome are institutionalized through robust intergovernmental agreements and extensive industrial cooperation. Major Italian multinational corporations—most notably Eni—maintain a massive, long-standing operational footprint in Kazakhstan, expanding far beyond traditional oil and gas extraction into large-scale renewable energy infrastructure, solar and wind power plants, and industrial engineering projects [8].

Italy's economic diplomacy in Kazakhstan functions as a core pillar of its national energy security and industrial expansion, perfectly synchronized with the EU's broader connectivity objectives. For Kazakhstan, the influx of Italian capital and world-class technological expertise acts as a crucial anchor in maintaining its multi-vector foreign policy, balancing relations among major global actors. Joint ventures focusing on low-carbon energy infrastructure, environmental remediation, and logistics engineering demonstrate how Italian industrial engagement directly reinforces Kazakhstan's sustainable development goals and infrastructural upgrading [9].

Geopolitical Alignment, Sustainability, and Regional Connectivity. Infrastructure development in Kazakhstan operates as an instrument of modern geo-economics, enabling the country to navigate complex regional pressures and enhance its sovereign agency. Situated at the crossroads of Eurasia, Kazakhstan utilizes its cooperative frameworks with Western partners, particularly Italy and the wider EU, to modernize its transit architecture and reduce historical logistical vulnerabilities [10].

European-backed infrastructure projects act as vectors of regulatory harmonization, introducing rigorous European standards for environmental impact assessments, transparent public procurement, corporate governance, and technical safety into the Kazakh market. Furthermore, the strong emphasis on sustainable development ensures that transport corridors and energy grids are built to withstand future ecological and economic shocks. This convergence

of European strategic interests and Kazakh modernization objectives establishes a stable, resilient framework for long-term regional integration and sustainable prosperity in Central Asia.

Conclusion. The comprehensive analysis of Italy's prominent role in infrastructure development within Kazakhstan highlights a transformative shift in modern economic diplomacy, where physical and digital connectivity serves as the primary catalyst for long-term geopolitical and institutional integration. As a leading European partner in Central Asia, Italy goes far beyond traditional commercial engagement, utilizing state-backed industrial frameworks and major corporate capital as a strategic instrument of regional stabilization and bilateral convergence. The modernization of critical trade conduits, most notably the Trans-Caspian International Transport Route (Middle Corridor), underscores how Italian-backed infrastructural projects successfully bridge European strategic security demands with Kazakhstan's imperative for national economic diversification and modernization.

At the micro-level, the bilateral partnership between Kazakhstan and Italy exemplifies how national-level industrial statecraft and broader Mediterranean-European integration policies synergize with exceptional effectiveness. Anchored by major corporate entities like Eni and prominent engineering firms, Italy has driven vital investments not only in large-scale hydrocarbon and energy sectors but also in renewable power grids, advanced engineering, and sustainable urban infrastructure. This high-level industrial collaboration demonstrates that economic diplomacy achieves optimal results when rooted in technology transfer and sustainable development, directly supporting Kazakhstan's transition toward a low-carbon, highly connected economy.

Furthermore, Italian corporate engagement actively addresses critical structural bottlenecks within Kazakhstan's logistics and transit networks. By upgrading transportation hubs, modernizing pipeline networks, and investing in advanced transit systems, Italian enterprises contribute directly to the physical expansion of the Eurasian trade corridors. These targeted infrastructural interventions ensure that local supply chains remain robust, efficient, and capable of handling increasing volumes of international cargo moving between East and West.

In addition to physical infrastructure, these engagements play an indispensable role in reinforcing Kazakhstan's multi-vector foreign policy. By expanding its network of advanced Western partners like Italy, Astana successfully navigates complex geopolitical pressures, minimizes historical transit vulnerabilities, and bolsters its sovereign agency. Concurrently, Italian capital inflows introduce rigorous standards of environmental compliance, transparent procurement, and technical safety, fostering structural and institutional reforms that resonate deeply throughout the domestic economy.

The scope of bilateral cooperation extends increasingly into the realm of green transition and ecological sustainability. Italy's domestic expertise in renewable energy – particularly in solar, wind, and green hydrogen technologies aligns seamlessly with Kazakhstan's ambitious national targets for carbon neutrality and environmental remediation. Joint ventures in renewable power generation demonstrate that economic diplomacy can successfully pivot toward ecological resilience, ensuring that future infrastructure projects mitigate climate change while powering regional growth.

Beyond energy and transport, the partnership fosters vital human capital development and institutional capacity building. Italian engineering and corporate projects in Kazakhstan inherently require advanced technical training, specialized education programs, and knowledge-sharing initiatives for local workforces. This transfer of professional expertise builds an enduring foundation of technical competence, empowering local specialists and strengthening Kazakhstan's domestic labor market for generations to come.

Looking ahead, the sustained convergence of Italian and Kazakh interests along major Eurasian transport and energy corridors solidifies infrastructure development as an enduring pillar

of regional stability and mutual prosperity. Future cooperation will increasingly rely on the seamless execution of green energy transitions, digital connectivity projects, and resilient supply chain integration. Ultimately, the synergy between Italy's investment strategies and Kazakhstan's development objectives establishes a durable blueprint for twenty-first-century statecraft, proving that infrastructure diplomacy is a vital engine for sustainable Eurasian integration.

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Historical Sciences

THE HISTORICAL SIGNIFICANCE OF THE SWISS REFORMATION

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ABSTRACT

The reform movement was not limited to Germany alone. By the 1520s, and especially the 1530s, Lutheranism had spread to the Scandinavian countries and, to some extent, to England, France, Poland, and Hungary. Lutheranism exerted an even greater influence on Switzerland, Germany's southern neighbor. Here, a new system of Protestantism was developed, and a new church organization based on Reformation principles was established. The loose and ill – defined nature of the Swiss Confederation turned the state into a political pawn in the hands of major powers; the King of France, the Holy Roman Emperor, and the Pope all employed Swiss peasants as mercenary soldiers. Conditions were becoming ripe for the onset of the Reformation movement in Switzerland. In this process, the activities of Huldrych Zwingli and John Calvin deserve special mention. The Reformation that triumphed in Switzerland was not confined to the country's borders; it fostered an environment conducive to the emergence of qualitatively new, Europe – wide developments of a global nature. In this context, the formation of the Westphalian system – which formalized the creation of the new, independent Swiss state on the European stage – is of particular interest.

Keywords: Swiss Confederation, Reformation, Europe, global change, religious teachings, historical significance

Introduction

A confederation of cantons was established in Switzerland in the late 13th century. The events that began in Uri, Schwyz, and Unterwalden expanded further over time, and by the mid-14th century, Zug, Glarus, Zurich, and Bern had joined them. In the 15th century, the Swiss confederation established an independent state through its struggle against the German Habsburgs and the feudal lords of Northern Italy and Western France. The alliance emerged victorious in the Swabian War; under the Treaty of Basel of 1499, it was exempted from Imperial obligations, and its ties to the Empire became merely formal.

The treaty of 1511 confirmed Switzerland's independence. Following the incorporation of Basel, Schaffhausen, and Appenzell, Switzerland expanded to comprise 13 full – fledged cantons and 10 independent territories. Among Swiss cities, Geneva held a special place as a center of industry and trade; it joined Switzerland in 1530 after being liberated from the Duchy of Savoy.

As a confederation, Switzerland lacked permanent central governing bodies, a common currency, an army, a flag, and a state seal. The Tagsatzung was considered the supreme authority; by the late 15th century, Zurich held the leading role within it.

Within the confederation, the cantons, federal territories, and vogteien – along with their respective urban and rural communities – constituted the core components of the political – administrative system. In the cities, the primary governing bodies were the Great Council, the Small Council, and the magistracy (comprising the burgomaster, the college of schöffen, and

various sectoral commissions). Cooptation – whereby an elected body adds new members to its ranks without a formal election – was widely practiced. Magistrates were reelected annually.

Under the treaty concluded with King Francis I of France, the hiring out of troops became a major state – level enterprise (involving 80.000 soldiers and generating 40.000 – 50,000 gold ecus annually⁰). Despite prohibitions, the ruling oligarchs of Zurich, Bern, and Basel grew wealthy on the proceeds from this trade and held a dominant position within the Confederation.

The Economic Situation in Switzerland

The economic character of the various cantons and territories was not uniform. Common features shared by most of them included the preservation of rural communities (marken) and a large number of free peasants, alongside the limited development of feudal relations. In the “forest” (rural) cantons – such as Schwyz, Uri, and Unterwalden – extensive crop farming was not profitable; instead, livestock farming came to the fore as roads and trade developed.

During the wars of independence in the 13th and 14th centuries, the majority of rural cantons acquired lands from the feudal lords, and the peasants gained their freedom. Although commodity – based agriculture developed in some regions, feudal land relations and various forms of peasant dependency persisted in many hiliwicks.

The situation was different in the urban cantons of Zurich, Basel, and Bern, as well as in the allied territories of Geneva and St.Gallen. Grain cultivation and the growing of industrial crops were successfully carried out and were market – oriented. Feudal land relations and forms of peasant dependency were widespread. Common lands (allmenden) had been appropriated by the rural elite. Peasants were required to sell their surplus grain at their respective urban markets.

Swiss cities were not numerous. Guild – based craftsmanship flourished within them. In Basel, four of the fifteen guilds – comprising merchants, money changers and goldsmiths, and winemarkers and wine merchants – held special privileges. The Saffron Guild united more than thirty skilled masters. In Geneva, the guilds were abolished during the Reformation [Image 1].



Image 1. Old map of Switzerland from Ortelius` atlas, 16th century

The guild system in Swiss cities was disintegrating. Sectors such as textiles were coming under the control of merchants. In new industries – such as book printing, haberdashery, and the production of silk and paper – guilds either did not exist, or the guild structures in place allowed for entrepreneurial activity. French and Italian Calvinist migrants were the organizers in these fields.

Switzerland held a significant place in pan – European transit trade connecting Antwerp, major French commercial cities, and the empires of the Mediterranean basin. Swiss fairs, which

flourished in the 15th century, ceased operations by the mid – 16th century. The Zuzach fairs, linked to Leipzig, Frankfurt, and Lyon, thrived. This fostered the development of a commercial credit system; banks were established in Basel in 1504 and in Geneva in 1568.

The Onset of the Reformation in Switzerland

In the early 16th century, Swiss cities increased pressure on their rural districts, allied territories, and bailiwicks, curtailing their administrative and judicial rights as well as their freedoms. In the late 15th century, Bern had abolished serfdom in rural areas and standardized the status of various peasant groups. Socio – economic development was generating tension in the country. Unrest and uprisings occurred during the late 15th and early 16th centuries. In this regard, the events that took place in Zurich, Lucerne, Solothurn, and other locations between 1513 and 1515 are particularly noteworthy.

The cantonal authorities continued to exert pressure on the Church. By the end of the 15th century, they had consolidated control over the appointment of clergy and the administration of church and monastic lands. In the Forest Cantons, patriarchal traditions, mercenary military service, and the influence of France, the Habsburg Empire, and the Papacy fostered socio – economic stagnation and reinforced the position of Catholicism. The Forest Cantons remained untouched by the Reformation.

In the city cantons and allied territories, resistance was mounting among the increasingly bourgeois burgher class against the ruling guild oligarchies; opposition to the practice of sending mercenaries to serve in foreign lands was growing, and the influence of humanist ideas was on the rise. The interests of these circles were intertwined with Europe's progressive traditions of socio – economic development. The concept of transforming Switzerland into a broader federation – spearheaded by Zurich and Bern – was gaining momentum. The University of Basel was becoming a bastion of humanism and secular culture; during the first three decades of the 16th century, figures such as Erasmus of Rotterdam, Sebastian Brant, and Beatus Rhenanus were associated with the institution, while publishers like Froben and Amerbach were actively engaged in publishing humanist literature.

Huldrych Zwingli, his teachings, and the completion of the Zwinglian Reformation in Switzerland

At the forefront of the Swiss Reformation stood Huldrych Zwingli (1484 – 1531) [Image 2], who came from a wealthy peasant family and was educated at the universities of Vienna and Basel. After graduating from the University of Vienna, he taught Latin in Basel, where he became acquainted with humanist ideas. Zwingli served as a religious leader in the city of Glarus. In 1515, he served as a chaplain with Swiss troops and took part in the Battle of Marignano, which ended disastrously for the Swiss; following this experience, he developed a negative attitude toward mercenary service.



Image 2. The Zurich reformer Huldrych Zwingli in a portrait by Hans Asper (1549)

He had been advancing his ideas since 1516. His embrace of the Reformation occurred following Luther's actions in 1517. Upon returning to Zurich, Zwingli did not immediately sever ties with the Catholic Church; instead, he largely confined himself to criticizing its doctrines. Unlike Luther, Zwingli was distinguished by his tolerance, humanism, and dialectical outlook. He favored synthesis over the mechanical categorization of concepts, regarding phenomena such as nature and society, or cognition and faith, as various facets of broader, global realities (I believe in order to understand).

The concept of divine predestination held a central place in Zwingli's doctrine. It could apply to all true members of the church (a point of difference between the theories of Zwingli and Luther).

Like Martin Luther, Zwingli based his teachings on the Bible. He opposed the sale of indulgences and the veneration of saints. At Zwingli's urging, the authorities in Zurich banned the sale of indulgences within their canton. Consequently, Zwingli's relationship with the Pope deteriorated and was ultimately severed.

Zwingli's political stance differed sharply from Luther's. A patriot from a young age, Zwingli grounded his views in republican principles; this was particularly evident in his anti-Habsburg propaganda. He regarded the implementation of political and social changes as the responsibility of secular authority. Zwingli considered obedience to tyrants a grave sin.

Zwingli rejected monastic lands and opposed usury and the practices of serfdom; however, he advocated for the preservation of small-scale property ownership. His teachings spread widely among burghers, the urban plebs, and the peasantry.

According to Zwingli, secular authority and laws were established to eliminate crime and wrongdoing; they are just only when they implement divine laws. Otherwise, the government must be changed. Like Aristotle, Zwingli regarded the aristocratic state as the best form of government. The authorities, elected annually, were required to rely on the people and Zwingli's church, and to act in accordance with divine laws.

Zwingli published his reformist principles in 1523 in a pamphlet titled the "67 Articles".

In January 1523, Zwingli proclaimed his teachings – much like Luther – and presented them to the city patriciate for implementation. The city council abolished fasting and clerical celibacy, and ties with the Bishop of Constance were severed. Zwingli renounced temporal authority and consented to concessions regarding peasants' feudal obligations, as well as to negotiations concerning issues such as Anabaptism in Zurich.

In 1523, the magistrate issued a directive regarding the confiscation of church and monastic properties and the reorganization of the monasteries. Although this directive was carried out, the obligations of the monastic peasants remained unchanged, giving rise to discontent between the peasants and the townspeople. That same year, Zwingli emerged victorious in two disputations.

In 1524 – 1525, the celebration of Mass was halted in Zurich, icons and other sacred objects were removed from churches, and monasteries were closed with their assets transferred to secular authorities; the rules for selecting church leaders were altered, allowing the laity to elect the clergy themselves. Usury was banned, and the hiring of mercenary troops was abolished. Patricians and nobles were excluded from the fully democratized magistracy. Adherence to Zwinglianism was made mandatory for all members of the canton.

The Reformation was completed in Zurich in 1525 and triumphed in Bern and Basel in 1528. While concessions were made to the peasantry in Bern, the political structure in Basel remained unchanged. Zwinglianism prevailed in Schaffhausen, St.Gallen, and Glarus. The confessional and political division of Switzerland reached its peak. Protestant alliances (Zurich, Bern, Schaffhausen, Constance) and Catholic alliances (Schwyz, Uri, Unterwalden, Lucerne, and Valais) were reformed, and an agreement was reached with Austria.

Emboldened by victory, Zwingli sought to establish a powerful federation of Protestant cantons and Imperial princes in the heart of Europe. A meeting convened in Marburg in 1529 to this end ended in failure; Luther, defending his own ideas, refused to compromise with Zwingli. Unwilling to prolong the matter, Zwingli marched an army to Kappel that same year to break the resistance of the Catholic alliance and achieved victory. Under the Treaty of Belgor (1529), the alliance between the Catholic cantons and Austria was dissolved, and the Reformation was implemented in the jointly administered bailiwicks.



Image 3. The Second War of Kappel (1531)

During the Second War of Kappel in 1531 [Image 3], the objective of dismantling the Catholic cantonal alliance was not achieved, and Zwingli was killed. Under the Second Treaty of Kappel (1531), the Protestant cantonal alliances were dissolved. The center of the Reformation shifted to southwestern Switzerland. Thereafter, the issues of the country's political centralization and national unity remained unresolved for centuries.

Changing Political Situation

A crisis situation emerged during the first three decades of the 16th century. Uprisings occurring between 1520 and 1526 put an end to the secular authority of the Bishopric of Geneva. Geneva's position on trade and strategic routes led to interference in its affairs by France, the Empire, and Savoy. In response, the city established alliances with Bern, Basel, and Zurich, and the Reformation party intensified its activities. After the suppression of the 1524 Lyon uprising, French supporters of the Reformation arrived here. In February 1528, Reformation supporters – led by the French – born Farel and Froment – triumphed in a public debate. The period from 1532 to 1536 was marked by severe clashes between Catholics and Reformers. Following Farel's victory in the 1535 debate, the Catholic Mass was abolished, and the bishop left Geneva. In 1536, the city council officially adopted the Evangelical faith. Confiscated monastic property was used for

charitable purposes. Only Sundays were observed as holidays. Those who failed to attend Sunday sermons were fined.

The Activities of John Calvin as a Historical Figure

Another prominent reformer, John Calvin (1509 – 1564) [Image 4], was active in the Swiss city of Geneva. He was born in Noyon, Picardy, into the family of a church official – specifically, a church prosecutor. Wishing for him to become a lawyer, his father sent him to study first at the University of Bourges and later at the University of Paris. Calvin received a solid classical education, mastered ancient languages, and became a staunch Protestant. Due to religious persecution, Calvin left France, living first temporarily in Strasbourg, Germany, and later in Basel. Subsequently, he was invited to Geneva. His work titled “Institutes of the Christian Religion” (1536) was published in Basel. In this book, Calvin provided a systematic exposition of the fundamentals of Protestantism.



Image 4. John Calvin (1509 – 1564)

In 1536, Calvin, together with Farel, drafted the “Articles on the Governance of the Church”. These articles outlined the structure and rituals of the new church. The church was based on parish communities, with councils of elders and consistories operating at the local level. Coercive measures were enforced solely by secular authorities, and the nature of their interaction with the church was defined. A special morality police force was established.

Calvin advocated the principle that church authority should take precedence over state authority. This policy provoked strong opposition from the burghers of Bern. According to one account, this was the reason – while another attributes it to a change in government – that Calvin was forced to leave the city alongside Farel. When the position of Calvin’s supporters strengthened again, the new city council recalled him in 1541, and Calvinism became firmly established in Geneva. Migrants from Northern Italy and France supported Calvin.

In his teachings, Calvin further developed the general tenets of the Reformation. While Luther and Zwingli had formulated the theory of divine predestination in general terms, Calvin focused primarily on its absolute and immutable nature. He regarded strict adherence to the tenets of Calvinism – along with a pious and active life lived in God’s name – as the sign of having

been predestined for eternal happiness. Framing the issue in this way eliminated fatalism and passivity, convinced Calvinists of their divine election, and inspired them to fulfill their duties with all their might. Through this, the divinity within the individual manifested itself, independent of human will.

According to Calvin, a person could be saved from all sins solely through the will of the Creator. God had predestined some people for salvation and others for destruction. All people in the world were divided into two categories: the privileged and the wretched. In Calvin's view, God became a formidable, living presence that determined the fate of individual human beings and the world itself.

Calvin's doctrine was directed against both Catholicism and the radical movements of popular reformers. He labeled the popular reformers as godless and materialists. Calvin maintained that one's fate does not depend on a person's evil or good deeds. God created some people to acquire worldly wealth, while others are destined to endure eternal suffering. Individual effort is of no avail in escaping this suffering; no one has the power to determine their future destiny, nor can a person alter their fate. According to Calvin, poverty is a test of faith in God. In this regard, Calvin's teachings fostered passivity and justified a class – based society. He instilled in the poor the idea that they could improve their circumstances by working diligently for their masters – an act that would be pleasing to God.

The system of socio – economic and ethical norms within Calvinism was intrinsically linked to the doctrine of divine predestination. He even attempted to establish a Calvinist colony in Brazil with the aim of spreading the true faith.

Calvin approached issues regarding the social structure of the state and society with great caution. He criticized monarchs, princes, and feudal lords for their acts of violence. He believed that if a head of state established a regime of violence and tyranny, they were thereby violating religious laws and showing disrespect to the church. Such individuals would, sooner or later, incur God's wrath. However, Calvin did not extend the struggle against tyranny to the masses. He assigned this role to the church and a representative assembly – the States General. Calvin considered democracy the worst form of government and justified an aristocratic structure. Accordingly, power in Geneva was concentrated in the hands of a select group of people.

According to Calvin, both the individual and society are flawed and imperfect. The state was established by divine decree to govern them. The ruler's authority is constrained by divine will and the necessity of ensuring the welfare of their subjects. Unjust rulers face divine retribution and popular uprising. Calvin approached the issue of resistance to tyranny with extreme caution, believing that such a right should belong to representative bodies of the estates. The use of force was permissible only in exceptional cases where all forms of legal and passive resistance had failed. On this basis, Calvin did not support the Huguenots' 1560 plot against the King of France (the Conspiracy of Amboise). In Calvin's view, oligarchy was considered the best form of government, while democracy was deemed the worst.

The church had to safeguard its spiritual independence from state authority. The Calvinist church was organized based on republican principles, Congregations were led by elders – drawn from wealthy laypeople – and experienced preaching ministers. This council, known as the consistory, oversaw the religious affairs of the community. Matters concerning Calvinist doctrine were resolved in special assemblies of ministers called congregations. These congregations later evolved into local and national synods. Their primary objective was to combat deviations from orthodox doctrine and to oppose heresy. Deacons were responsible for collecting levies and allocating funds toward church reserves and charitable activities.

Calvin severely persecuted the Anabaptists. He opposed their demands for the communal ownership of property and the abolition of all forms of authority, labeling these demands "shocking barbarity".

Drawing conclusions from the political situation in early 16th century France, Calvin initially advocated for the subordination of secular authority to the church. However, during the course of the Reformatoin movement in Geneva, he modified his views and accorded significant precedence to secular authority.

Conclusion

The Swiss Confederation, which took shape as an independent state in the 16th century, became part of the European state system. The Reformation, spreading across Europe at the time, also extended to Switzerland. Zwinglianism – a movement that primarily reflected Swiss issues – was ultimately defeated. Its attempt to transcend Swiss borders and become the guiding ideology for the reforming Swiss cantons and Imperial principalities proved unsuccessful. At the same time, favorable internal conditions for this were lacking. A crisis soon arose due to the weak foundations of industry, crafts, agriculture, banking, and trade – industrial companies, a shortage of capital, and the fact that entrepreneurial activities were largely carried out by citizens of France and Northern Italy. Reality demanded adaptation to the new circumstances. Zwingli's successor, Bullinger, eventually made concessions to Calvin, and this was reflected in the texts of the common confession of faith.

Geneva became a springboard for Calvinism. During this period, Calvinism – the religion of the boldest segment of the bourgeoisie – reflected demands arising not merely from the Swiss cantons, but from pan – European historical processes across all spheres, including social – ideological priorities and moral norms and codes. Consequently, in contrast to Zwinglianism, it emerged onto the European stage. Amidst the fierce struggle between progress and feudal reaction, the republican and organizational principles of Calvinism were employed by French Huguenots againts absolutism and by Polish nobles against royal authority. Along with its adherents, Calvinism also spread to the colonies held by European states [Image 5].



Image 5. The map of Switzerland by Hans Conrad Gyger (1599 – 1674), compiled in 1683, was intended for military purposes and therefore long held the status of classified material

The Reformation teachings in Switzerland were part of a social, political, and ideological movement that swept across all Western European countries in the 16th century. The two Reformation movements that emerged in Switzerland did not hold equal historical significance. Zwinglianism failed to transcend its local context; it gradually lost its militant spirit and evolved into a typical burgher Reformation.

Calvinism was a major religious movement that spread across Europe. It became most widespread in countries transitioning toward the development of capitalism. Calvinism served as the religious, philosophical, and political ideology of the emerging bourgeoisie. It exerted a significant influence on the outbreak of the Dutch bourgeois revolution in the 16th century and the English bourgeois revolution in the 17th century. The Calvinist denomination clearly reflected the class – based maturity of the bourgeoisie during the era of the manufactory system. Like other religious ideologies, Calvinism possessed distinctive characteristics. Consequently, it was embraced by both the bourgeoisie and European feudal circles. They highly valued Calvinism's socio – ethical and philosophical perspectives, while also leveraging the movement's republican and organizational principles to serve the interests of royal governance.

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Culturology

ПОСТКОЧЕВАЯ ИДЕНТИЧНОСТЬ: ЧТО ОСТАЛОСЬ ОТ КОЧЕВОГО МИРА В СОЗНАНИИ ГОРОДСКИХ КАЗАХСТАНЦЕВ XXI ВЕКА

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Современный Казахстан переживает масштабную и ускоренную трансформацию социальной и культурной структуры, связанную с урбанизацией, цифровизацией и включением в глобальные процессы. За сравнительно короткий исторический период общество прошло путь от кочевого и полукочевого образа жизни к доминированию городских форм существования. Этот переход оказался не только социально-экономическим, но и глубоко культурным, затронувшим способы мышления, самоидентификации и восприятия мира. В результате возникло особое состояние, при котором внешне модернизированное общество продолжает опираться на глубинные культурные основания, сформированные в кочевом прошлом.

В научных исследованиях, посвящённых идентичности современного Казахстана, широко используется тезис о её гибридном характере. Подчёркивается переплетение кочевого наследия, советского модернизационного опыта и глобальных культурных влияний. Однако подобные интерпретации зачастую остаются на уровне обобщённых характеристик и не раскрывают механизмов функционирования кочевого культурного кода в условиях городской среды. В результате кочевая культура либо рассматривается как утраченная традиция, либо сводится к фольклорным, символическим и репрезентативным практикам, не затрагивая глубинные уровни сознания и повседневного поведения.

Настоящее исследование исходит из иной исследовательской позиции. В центре внимания находится не вопрос о том, сохранилась ли кочевая культура, а анализ того, какие именно элементы кочевого мира продолжают существовать внутри городской ментальности и каким образом они были трансформированы. Речь идёт о глубинных установках и смысловых структурах, которые редко осознаются самими людьми, но устойчиво проявляются в отношении к пространству, мобильности, социальной принадлежности, коллективности, свободе и автономии. Эти элементы не воспроизводятся напрямую, однако продолжают функционировать как внутренний культурный код, влияющий на повседневные практики и формы самоидентификации.

Актуальность данной темы обусловлена тем, что процессы урбанизации и глобализации в Казахстане происходят с высокой скоростью, формируя новые типы городской культуры и социальной мобильности, особенно среди молодёжи. В этих условиях посткочевая идентичность не только не исчезает, но приобретает новые формы выражения,

включая цифровые практики, символическое освоение пространства и альтернативные модели социальной связанности. Анализ этих процессов позволяет по-новому взглянуть на специфику казахстанской идентичности, выходя за рамки противопоставления «традиционного» и «современного».

Целью статьи является выявление и интерпретация трансформированных элементов кочевого сознания, сохранившихся в условиях городской среды Казахстана XXI века, а также описание механизмов их адаптации к современной социальной реальности. Объектом исследования выступает идентичность городских казахстанцев, предметом — посткочевые культурные установки, проявляющиеся в мышлении, поведении и символических практиках.

Теоретическую основу исследования составляют концепции гибридных идентичностей, культурной памяти и посттрадиционных обществ, а также труды по антропологии кочевых цивилизаций Евразии. Методологически работа опирается на междисциплинарный интерпретативный подход, позволяющий рассматривать идентичность как динамическую и многоуровневую структуру. Научная новизна исследования заключается в рассмотрении посткочевой идентичности не как следа исторического прошлого, а как активного культурного механизма, структурирующего современную городскую ментальность Казахстана.

Изучение посткочевой идентичности в современном городском обществе Казахстана представляет собой междисциплинарное направление, пересекающее культурологию, социологию, урбанистику и цифровую антропологию. Литературный массив, посвящённый данной теме, охватывает как исследования традиционной кочевой культуры, так и работы, посвящённые трансформации культурных кодов в условиях урбанизации и цифровизации.

Одним из ключевых направлений в историографии является изучение наследия кочевого образа жизни и его влияния на современные социальные практики. В работах таких исследователей, как Хазанов (2016) и Масанов (1998), подчёркивается, что кочевая логика — ориентация на путь, мобильность, автономию и коллективную ответственность — сохраняется в сознании людей даже после перехода к оседлому образу жизни. По мнению Хазанова, переход к оседлости не уничтожает номадическое мышление, а лишь меняет формы его проявления (Хазанов, 2016). Исследования Масанова также показывают, что родовая структура, утратив внешние социальные функции, продолжает оказывать влияние на психологию и способы взаимодействия в городских сообществах (Масанов, 1998).

Другим направлением является изучение гибридных идентичностей и процессов посттрадиционных обществ. Работы Гидденса (2000) и Бхабхи (2011) рассматривают идентичность как динамическую категорию, формируемую на стыке традиционного и современного, локального и глобального. В казахстанском контексте это проявляется в том, что городские жители одновременно сохраняют эмоциональную связь с «родом» и степью, участвуют в цифровой культуре и используют глобальные социальные практики. Как отмечает Бхабха, пространство между культурами является источником новых форм идентичности (Бхабха, 2011), что непосредственно соотносится с феноменом посткочевой идентичности.

Отдельное внимание уделяется исследованию городской мобильности и её роли в трансформации кочевых установок. Кастельс (2001) подчеркивает, что в сетевом обществе пространство потоков начинает доминировать над пространством мест, что в контексте Казахстана позволяет трактовать городскую жизнь как продолжение кочевого мышления, где мобильность и смена социальных ролей являются органичной частью идентичности. Анализ Джуманова (2022) и Ахметовой (2020) показывает, что молодёжь активно использует цифровые платформы, социальные сети и фриланс, воспроизводя кочевую логику автономии и движения в современном цифровом контексте.

Многочисленные исследования посвящены роли родовой логики и социальных связей в городской среде. Сейфуллин (2018) и Шарипова (2019) подчеркивают, что хотя прямое воспроизведение родовых структур исчезло, их психологические и социальные функции сохраняются через эмоциональные связи, взаимопомощь и формирование временных сообществ. Эта трансформация позволяет говорить о сохранении ключевых смысловых кодов кочевого сознания, но в адаптированной, символической форме.

Другим аспектом литературного дискурса является символика степи в городской и цифровой культуре. Кулиева (2013) отмечает, что образ степи продолжает выполнять функцию внутреннего символического пространства свободы, которое выражается в эстетике музыки, визуальных медиа и социальных сетей. В цифровой культуре это проявляется через визуальные практики, мемы и видеоконтент, формирующие эмоциональную и культурную связь с традицией кочевого мира (Нургалиева, 2020; Джуманов, 2022).

Поколенческое измерение посткочевой идентичности является ещё одним важным направлением. Мухамеджанова (2021) показывает, что старшее поколение осознаёт связь с кочевым прошлым через память, семейные истории и соблюдение традиционных ценностей. Среднее поколение использует эти установки для адаптации к городской жизни, формируя гибридные модели поведения. Молодёжь же проявляет посткочевую идентичность в скрытой, символической форме, через мобильность, цифровые практики и участие в эмоционально близких сообществах (Юсупов, 2021; Ахметова, 2020).

Обобщая литературный обзор, можно выделить несколько ключевых тенденций научной дискуссии: сохранение глубинных установок кочевого сознания (мобильность, автономия, родовая принадлежность) в городской среде; формирование гибридной идентичности в условиях посттрадиционного общества и глобализации; адаптация родовой логики и коллективной ответственности в форме эмоционально близких и временных сообществ; символическое сохранение степного пространства как культурного и эстетического кода; передача посткочевой идентичности через поколения в адаптированной, неосознанной форме; цифровая среда как новая среда функционирования посткочевой идентичности.

Таким образом, обзор литературы демонстрирует, что посткочевая идентичность в современном Казахстане является устойчивой культурной категорией, которая трансформируется в условиях урбанизации, цифровизации и глобальных процессов, сохраняя при этом ключевые ментальные установки кочевого прошлого. Для дальнейших исследований важно учитывать как структурные изменения городской среды, так и психологические и символические механизмы передачи культурного наследия.

Данное исследование носит теоретико-интерпретативный характер и направлено на анализ посткочевой идентичности как культурного кода, функционирующего в условиях городской среды Казахстана XXI века. Методологический подход основан на междисциплинарном синтезе культурологии, социальной антропологии, социологии и исследований городской и цифровой культуры.

Теоретической базой исследования послужили концепции культурной памяти (Я. Ассман), посттрадиционного общества (Э. Гидденс), гибридных идентичностей (Х. Бхабха), сетевого общества и мобильности (М. Кастельс). Эти подходы позволяют рассматривать идентичность не как статичную характеристику, а как динамическую систему смыслов, трансформирующуюся в условиях урбанизации и цифровизации.

Эмпирическим материалом исследования выступают культурные тексты и символические практики, репрезентирующие городскую идентичность: медиатексты, визуальный контент социальных сетей (Instagram, TikTok), художественные и публицистические материалы, а также описания современных социальных и

профессиональных практик городской молодёжи Казахстана. Анализ охватывает период 2018–2024 гг., что позволяет проследить актуальные формы воспроизводства посткочевого культурного кода.

Основными методами исследования являются качественный интерпретативный анализ, дискурсивный анализ культурных нарративов и символов, а также сравнительный анализ поколенческих моделей идентичности. Особое внимание уделяется выявлению устойчивых смысловых структур (мобильность, путь, родовая логика, коллективность, автономия), которые сохраняются вне реального кочевого быта и проявляются в городской и цифровой среде.

Выбор данной методологии обусловлен задачей выявить не внешние формы воспроизводства традиции, а внутренние культурные установки, интегрированные в повседневное мышление и практики городских жителей. Такой подход позволяет рассматривать посткочевую идентичность как активный культурный механизм, а не как символическое наследие или декоративный элемент национальной культуры.

Посткочевая идентичность не является прямым наследием кочевой культуры, но и не сводится к её исчезновению. Это новая форма существования старых смыслов в городской среде, где они адаптировались к реалиям XXI века. Посткочевая идентичность — это не ностальгия по степи или декоративное воспроизведение традиций, а активная система смыслов, влияющая на поведение, мышление, социальные практики и символическую жизнь современного казахстанца.

Городской казахстанец живёт в логике «и-и», объединяя в себе противоречивые качества: он одновременно современный и традиционный, рациональный и эмоционально-кодовый, индивидуальный и родоцентричный. Такое состояние не является конфликтным, а представляет собой естественную форму социального существования общества, которое всего за одно поколение прошло путь от кочевой культуры к урбанизации.

Исследовательский интерес заключается не в выяснении, сохранились ли кочевые практики в буквальном смысле, а в том, как эти практики и ценности трансформировались, как они функционируют в современных городских реалиях. Несмотря на отсутствие реального кочевого быта, в сознании людей сохранились несколько глубинных установок, которые проявляются в поведении, мышлении, социальных ожиданиях и даже цифровой культуре.

Одним из центральных проявлений посткочевого идентичности является восприятие пространства и пути. Городской человек XXI века не живёт в юрте и не перемещает стада по степям, но его мышление продолжает опираться на категорию пути — как символа движения, свободы, личной автономии. Молодёжь стремится к мобильности, путешествиям, экспериментированию с карьерой и учебой, поиску возможностей «уехать — вернуться — снова уехать». Эта потребность к свободе не является западной модой, а глубинным наследием кочевого мышления, переведённым в язык глобальной урбанизированной жизни.

Другим важным аспектом является родовая логика. В городской среде прямые родовые структуры перестают быть социальным механизмом, но глубинное ощущение принадлежности сохраняется и проявляется в формировании городских мини-общностей, основанных на эмоциональной близости и взаимной поддержке. Род как психологическая опора становится инструментом социальной идентификации, влияя на дружеские связи, профессиональные сообщества и даже цифровое взаимодействие через социальные сети.

Также важно отметить сохранение ценностей гостеприимства, коллективности и уважения к старшим, которые в городских реалиях трансформируются в практики социальной гибкости. Способность быстро находить общий язык, объединяться вокруг

проектов, поддерживать тех, кто оказался в трудной ситуации, демонстрирует, что кочевой код выжил, но в новой функциональной форме.

Наконец, образ степи как символ внутренней свободы и корней адаптировался в культурную и эстетическую сферу. Он проявляется в музыке, кино, поэзии и цифровых практиках, таких как TikTok и Instagram, где молодёжь создает визуальные и нарративные образы бескрайних просторов, внутренней гармонии и автономности. Степь стала не физическим, а символическим пространством воображения, через которое сохраняется связь с прошлым.

Посткочевая идентичность формирует гибридную структуру современного сознания, где прошлое и настоящее переплетаются, создавая уникальный культурный код. Эта часть статьи создаёт основу для дальнейшего анализа конкретных проявлений кочевых категорий в городской среде, поколенческих различий и цифровой адаптации кочевого наследия, которые будут рассмотрены во второй и третьей частях основной статьи.

Современный городской житель Казахстана живёт в пространстве, где кочевой код проявляется в самых разных, иногда незаметных аспектах повседневной жизни. Главная особенность посткочевой идентичности заключается в том, что она не выражается напрямую через традиционные практики или внешние символы кочевого мира. Вместо этого её элементы интегрированы в повседневные решения, социальные взаимодействия и организацию личного времени.

Одним из ключевых проявлений остаётся мобильность. В отличие от западного представления о перемещении как необходимости или элементе карьеры, мобильность городских казахстанцев имеет глубокие культурные корни. Молодёжь рассматривает переезды, путешествия и смену работы не просто как адаптацию к обстоятельствам, а как естественное продолжение внутреннего кочевого пути. Это проявляется в привычке к «мини-путешествиям», командировкам, смене районов проживания или даже городов без ощущения разрыва с корнями. В социальных сетях активно демонстрируются маршруты поездок, фотографии с различных точек страны и мира, что отражает стремление к исследованию и открытию нового, схожее с кочевым освоением пространства.

Не менее важна социальная структура, трансформированная из родовой логики кочевого общества. В современных городских условиях род больше не выполняет институциональные функции, но продолжает существовать как психологическая и культурная матрица. Люди формируют «свои круги» в рабочих коллективах, учебных группах или онлайн-сообществах, где доверие, взаимопомощь и эмоциональная близость играют решающую роль. Например, молодые специалисты IT-сферы создают неформальные команды, объединяясь для совместной работы над проектами, обмена опытом или поддержки в сложных ситуациях — это современная форма ситуативной коллективности, характерной для кочевых сообществ.

Цифровая среда стала новым пространством кочевого опыта. Онлайн-платформы, соцсети и мессенджеры позволяют одновременно участвовать в нескольких «социальных пространствах», что воспроизводит мобильность и многоплановость кочевого мира. Молодёжь активно использует возможность быть частью разных культурных, профессиональных и социальных контекстов, сохраняя при этом ощущение целостной идентичности. Цифровой кочевник, работающий удалённо, создаёт жизнь по принципу «путь важнее места», что удивительно точно отражает структуру кочевого сознания: человек одновременно автономен и связан с сообществом.

Особое внимание следует уделить гостеприимству и коллективной ответственности, которые в городских условиях трансформируются в практики социальной гибкости. Например, жители многоквартирных домов и арендованных квартир активно поддерживают соседей, объединяются вокруг проектов или волонтерских инициатив, помогают в кризисных

ситуациях. Эти формы взаимодействия не закреплёны формально, но проявляются через личные инициативы и эмоциональные связи, отражая структурные принципы кочевого общества: способность объединяться временно ради общей цели.

Другой важный элемент — образ степи, который в городской среде функционирует как символ внутренней свободы и эмоциональной глубины. В визуальной и музыкальной культуре молодёжи степь стала эстетическим образом: это проявляется в контенте TikTok, YouTube, музыкальных клипах, уличном искусстве. Степь не воспринимается как географическая данность, а как пространство для воображения и личной автономии, символ корней, внутреннего покоя и широты жизненной перспективы.

Также сохраняется логика пути, которая проявляется в гибкости жизненных сценариев. Молодые казахстанцы не воспринимают жизнь как линейную последовательность: образование, работа, семья, стабильность. Напротив, смена профессий, дополнительное образование, путешествия и пересмотр личных целей воспринимаются как естественная часть существования. Эта установка напрямую связана с кочевым циклом жизни, где движение и адаптация были залогом выживания и социального успеха.

В повседневной практике городского человека кочевой код проявляется и в социальных медиа: выбор кругов общения, виртуальных сообществ, участие в тематических группах. Эти цифровые связи воспроизводят родовую принадлежность в модернизированной форме. Участники сообществ ценят эмоциональную близость, доверие и поддержку, а не формальные роли и обязанности. Таким образом, род трансформируется из внешней социальной структуры в внутреннюю психологическую модель.

Можно отметить, что городская среда Казахстана не разрушает кочевой код, а трансформирует его. Мобильность, цифровые сообщества, коллективные практики, эстетика степи и логика пути — все эти элементы создают уникальную культурную среду, где посткочевая идентичность проявляется в повседневной жизни. Городской житель XXI века живёт в условиях сложного взаимодействия традиции и модерности, где кочевой код продолжается в новых формах, адаптированных к цифровой и глобальной реальности.

Одним из наиболее заметных проявлений посткочевой идентичности в городской культуре является символика степи и природных образов. Хотя современный городской житель почти никогда не сталкивается с реальной степью в бытовой жизни, она сохраняется в сознании как пространство внутренней свободы и эмоциональной автономии. В музыке современных исполнителей, от поп- и хип-хопа до этно-электро, часто используются мотивы открытого пространства, ветра и движения. Визуальные образы бескрайних просторов появляются в кино, фотографиях, видеороликах и даже в оформлении городских пространств — на стенах, в общественных местах и в цифровой среде. Эти эстетические элементы выполняют функцию внутреннего «воздуха кочевника», позволяя жителям города сохранять чувство связи с природным и культурным прошлым страны, даже находясь в бетонной среде мегаполиса.

Важным символическим элементом остаётся путь как метафора жизненного движения. В художественных и литературных произведениях современных казахстанских авторов городские герои часто находятся в поиске, путешествуют, меняют пространство проживания и работу. Эти истории показывают, что логика пути — не просто способ перемещения, а глубокий культурный код, заложенный в сознании: жизнь понимается как движение, а не как статичное пребывание. Путь становится одновременно физическим, психологическим и социальным, отражая традиционную кочевую модель, адаптированную под современный городской контекст.

Фольклор и мифологические мотивы также остаются частью городской идентичности, но переживают значительную трансформацию. Городские казахстанцы воспринимают

старые легенды и предания не буквально, а как источник ценностей и символических моделей поведения. Например, уважение к старшим, мудрость и коллективная ответственность в мифах адаптированы под современные ситуации: на рабочем месте, в учебе, в социальных сетях.

Особое место занимает цифровая культура, где кочевой код проявляется в форме визуальных и текстовых символов. В социальных сетях и медиа-платформах популярны контенты с изображением степи, путешествий, исторических костюмов, юрт и родовых артефактов. Однако эти изображения не являются репрезентацией прошлого — они символические, эстетические, подчеркивающие чувство принадлежности, внутреннюю свободу и культурную самобытность. Цифровая среда превращается в новое «кочевое пространство», где личность может одновременно принадлежать разным сообществам и сохранять автономность.

Ритуальные практики также подверглись трансформации. В городской среде мало кто соблюдает традиционные кочевые обряды, но их элементы живут в современных формах: семейные праздники, встречи с друзьями, коллективные мероприятия приобретают форму символической памяти о роде и коллективной ответственности. Например, празднование Наурыза в городах не ограничивается традиционным набором обрядов, а становится культурным событием с акцентом на общность, гостеприимство и взаимоподдержку — все это отражает кочевой код в адаптированной городской форме.

Кроме того, городская молодёжь активно создает собственные эстетические коды, вдохновлённые кочевым прошлым. Это проявляется в моде, дизайне интерьеров, музыкальных клипах и визуальных проектах. Часто используются мотивы открытых пространств, природных текстур, геометрии традиционных орнаментов.

Особенно интересным является феномен «городской степи» как символического пространства. В социальных сетях и контенте современных казахстанцев степь становится пространством, где человек может «отключиться» от городской суеты, восстановить внутренний баланс и найти психологическую свободу. Этот символ одновременно связан с природой, историей и внутренней автономией, сохраняя глубинные элементы кочевого сознания.

В культурной и символической сфере посткочевая идентичность функционирует как живой культурный код, который позволяет городскому человеку сохранять связь с историческим прошлым, адаптируя его к современным условиям. Она проявляется не через буквальное воспроизведение кочевых практик, а через эстетические образы, ритуалы, цифровую культуру и ценностные установки. Эта трансформация показывает, что кочевой мир не исчез, а изменил форму, интегрировавшись в городскую ментальность, сохранив глубинную логику пути, родовой принадлежности и внутренней свободы.

Одним из ключевых аспектов посткочевой идентичности является поколенческая трансмиссия культурного кода. Старшее поколение сохраняет прямую связь с кочевым прошлым через воспоминания, семейные истории, традиции и устные рассказы. Эти элементы формируют определённые ценностные ориентиры — уважение к старшим, гостеприимство, коллективизм и чувство ответственности за род и сообщество. Для городского жителя старшего возраста эти ценности сохраняют форму «инструкций к жизни», которые помогают ориентироваться в социальных и семейных отношениях.

Молодое поколение, выросшее в урбанизированной среде, воспринимает кочевой код скрыто и символически, но не менее глубоко. Их связь с прошлым не проявляется через прямое соблюдение обрядов или бытовых практик, а через психологические установки, социальные привычки и поведение. Например, стремление к мобильности и путешествиям, создание «мини-родовых» сетей дружбы, поиск автономности и личного пространства — всё это трансформированные проявления кочевого логики, встроенные в современную

жизнь. Такой скрытый код проявляется в выборе учебы, карьеры, досуга и даже в цифровой активности, где молодежь формирует собственные сообщества и поддерживает социальные связи на основе доверия и взаимопомощи.

Социальная адаптация посткочевой идентичности в городских условиях проявляется через гибкость и способность к временным объединениям. В традиционном кочевом обществе люди объединялись для решения совместных задач — охота, пастбищное управление, защита стада. В городской среде аналогичные механизмы проявляются в форме проектов, стартапов, инициатив и общественных движений, где люди временно объединяются для достижения общей цели, после чего связи могут трансформироваться или растворяться.

Интересным феноменом является цифровая и глобальная адаптация кочевого кода. Современные IT-специалисты, фрилансеры и «цифровые кочевники» демонстрируют модель поведения, удивительно близкую к древнему кочевнику: мобильность, автономность, умение выстраивать социальные и профессиональные связи на расстоянии, способность к быстрой адаптации в разных контекстах. Этот феномен показывает, что кочевой код не исчез, а трансформировался в универсальную модель поведения, применимую в глобализированном мире.

Эстетическая и символическая интеграция кочевых элементов в городскую жизнь проявляется в повседневной культуре, творчестве и досуге. Городские жители используют образы степи, пути, родовой принадлежности и свободы для формирования своей идентичности. Музыка, кино, литература, визуальное искусство и социальные медиа становятся платформой, где прошлое и настоящее взаимодействуют, создавая уникальную культурную среду. Степь как символ внутренней свободы и пространство воображения, путь как метафора жизни, род как психологическая опора — всё это формирует когнитивный и эмоциональный каркас, обеспечивающий устойчивость идентичности в условиях урбанизации.

Посткочевая идентичность — это не воспроизведение кочевого уклада, а живой культурный код, который позволяет казахстанцу XXI века сохранять уникальную психологическую и социальную структуру. Она проявляется одновременно на нескольких уровнях: психологическом — стремление к автономности, мобильности, внутренней свободе; социальном — способность объединяться временными сообществами, поддерживать коллективные ценности, сохранять чувство принадлежности; эстетическом — использование символов, мотивов и образов кочевого прошлого в искусстве, медиа и повседневной культуре; цифровом — адаптация кочевых практик к современным технологиям, формирование новых форм общения и автономного существования.

Таким образом, современный казахстанец находится между двумя мирами — он не просто городской житель, полностью оторванный от исторического прошлого, и не прямой наследник кочевой культуры. Он живет в «пространстве между», где прошлое трансформируется в культурный код, способный действовать в современных условиях. Это «между» — и есть источник уникальности посткочевой идентичности, обеспечивающий устойчивость, гибкость и самобытность казахстанского общества в XXI веке.

В итоге, можно утверждать, что посткочевая идентичность не является пережитком или декоративной традицией. Она функционирует как динамическая система смыслов, которая влияет на поведение, мышление, социальные взаимодействия и эстетические практики городских жителей. Кочевой мир не исчез, а переосмыслился, сохранив глубинные коды: путь, род, свободу и коллективную ответственность. Городская культура XXI века, интегрируя эти элементы, создает уникальный социально-культурный феномен, который отличает казахстанское общество от других урбанизированных культур, сохраняя при этом связь с историческим и психологическим наследием кочевников.

TRADITIONAL “NEW VOICE”: Q-POP IN THE CULTURAL DYNAMICS OF CONTEMPORARY KAZAKHSTAN

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Abstract. This article analyzes the phenomenon of Q-POP in the context of cultural dynamics in contemporary Kazakhstan and the processes of post-Soviet nation-building. The novelty lies in identifying Q-POP as a complex space for symbolic negotiation and "cultural resistance," where new models of Kazakhstani national identity are formed through the interaction of state institutions, youth practices, and the tension between traditional and global values. The research task is to conduct a comprehensive analysis of the historical preconditions, institutionalization mechanisms, and hybrid nature of Q-POP as a form of glocalization, while examining youth cultural resistance practices and the genre's role in Kazakhstan's nation-building transformation.

The aim of the study is to understand Q-POP as a socio-cultural phenomenon and to determine its role in the formation of modern Kazakhstani identity. The work analyzes the mechanisms of cultural hybridization, the peculiarities of the institutionalization of the genre, the forms of symbolic autonomy of youth, and the specifics of linguistic and visual representation.

The methodological basis of the study consists of approaches to cultural studies and the theory of glocalization. The empirical base includes discourse analysis of official and media materials, content analysis of music lyrics and clips, as well as a comparison of Q-POP with the Korean model K-POP.

The results show that Q-POP is not only a reflection of sociocultural changes but also an active participant in the processes of redefining national identity. Combining global industrial forms with local cultural codes, the genre demonstrates the complex dynamics of interaction between institutional strategies and youth initiatives, which gives the study practical significance in the context of Kazakhstan's cultural policy.

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Keywords: Kazakhstan, Q-POP, nation building, soft power, glocalization.

Introduction

Following the collapse of the Soviet Union in 1991, the states of Central Asia were faced with the need to construct their own statehood, both institutionally and symbolically. The formation of sovereign political systems was accompanied by a re-evaluation of historical heritage, a revival of national and cultural traditions, and the consolidation of international agency. At the same time, new models of interaction with external actors were emerging, alongside a search for sustainable forms of national identity in the context of globalisation and the transnationalisation of the cultural sphere (Kim & Park, 2025; Anderson, 2006).

The processes of nation-building in the region are unfolding against a backdrop of a delicate balance between strengthening the titular nation as the foundation of statehood and the need to take account of the multi-ethnic structure of society. At the same time, the states of Central Asia are striving to overcome the perception of the region solely through the prism of the post-Soviet

space and to assert their own cultural and political agency on the international stage (杨成, 2012; Laruelle, 2015). In these circumstances, the formation of national identity is fraught with a number of contradictions: between the desire for international recognition and the preservation of cultural identity; between ethno-cultural identity and the formation of an inclusive civic nation; and between traditional cultural forms and the influence of global cultural industries (kun.kz, 2022; Joo-Yup Lee, 2015; Blakkisrud & Kuziev, 2019)

In a context described in a number of Western studies as the ‘black hole of world history’, the states of Central Asia objectively possess the potential to represent their own cultural distinctiveness more actively on the international stage, drawing on the region’s historical, cultural and civilisational characteristics (安德烈·贡德·弗兰克, 2016). One of the most telling areas in which these processes manifest themselves is the realm of popular culture. Against a backdrop of the widespread dissemination of transnational cultural models, pop music may contribute to a key instrument in the symbolic construction of identity and the cultural representation of the state (Street, 2012; Kudaibergenova, 2016; Schatz, 2004). In this context, the Q-POP phenomenon, which emerged in Kazakhstan around 2015, is of particular interest.

The Q-POP concept was proposed by the male idol group Ninety One and was originally positioned as a musical genre emphasising the national distinctiveness of Kazakhstan’s cultural output. The use of the Latin transcription ‘Qazaqstan’ symbolises both an appeal to national identity and a desire for global integration. In terms of genre and institutional structure, Q-POP represents a hybrid form combining elements of traditional Kazakh music, Western pop culture and the production model of the Korean K-POP industry.

Having gained widespread popularity among young audiences, Q-POP has become not only a musical genre but also a significant socio-cultural phenomenon. Its development reflects processes of cultural hybridisation, glocalisation and the transformation of youth identities in post-Soviet society (Jin, 2016). A space of symbolic competition is emerging around Q-POP, within which various social actors—state institutions, commercial cultural industries, conservative social groups and youth communities—interact.

The relevance of this research stems from the fact that an analysis of popular culture enables the identification of new mechanisms for the formation of national identity in the context of globalisation. The Q-POP phenomenon is a telling example of how global cultural industries adapt to local social and political contexts, shaping new forms of cultural representation and youth identity in post-Soviet societies.

The *aim* of this study is to conduct a comprehensive analysis of the Q-POP phenomenon as a cultural and social phenomenon in contemporary Kazakhstan, as well as to identify its role in the processes of nation-building, identity transformation and cultural modernisation in the post-Soviet period.

To achieve this aim, the following research *tasks* have been formulated:

- to analyse the historical and cultural preconditions for the emergence of Q-POP in the context of Kazakhstan’s post-Soviet transformation;
- to identify the characteristics of the genre’s cultural hybridisation as a form of glocalisation;
- to investigate the mechanisms of interaction between the state, cultural industries and social actors in the process of the institutionalisation of Q-POP;
- to identify forms of cultural and symbolic resistance manifested among young people through Q-POP practices;
- to assess the significance of Q-POP as an indicator of the transformation of nation-building processes in Kazakhstan.

The research hypothesis is that Q-POP functions not only as a musical genre but also as a space for cultural and symbolic negotiation, within which new models of national identity are formed, combining elements of tradition, global pop culture and youth cultural practices.

In this regard, the main research question is formulated as follows: how, in the context of the dynamics of nation-building in Kazakhstan, does Q-POP become a space of cultural and discursive competition, reflecting symbolic negotiations between the state, society and young people within the coordinates of 'tradition – modernity' and 'local – global'?

This study aims to analyse the mechanisms of interaction between state institutions, the commercial market, conservative groups and the youth audience in the process of the institutionalisation and symbolic interpretation of Q-POP. Particular attention is paid to the relationship between strategies of state incorporation and forms of cultural resistance.

Methods

The methodological framework of this study is interdisciplinary in nature and draws upon tools from cultural studies and the sociology of culture, as well as research on nationalism and globalisation. This choice is dictated by the very nature of Q-POP as a phenomenon situated at the intersection of cultural policy, the media industry and youth practices. In this sense, the study follows a broader research trend in which popular culture is viewed as a space for the production and re-imagining of identity (Jin, 2016; Lie, 2015; Kudaibergenova, 2017).

Theoretically, the study draws on Homi Bhabha's classical concepts of cultural hybridity (Bhabha, 1994) and Arjun Appadurai's concepts of global cultural flows (Appadurai, 1996). These approaches are not used in isolation, but in conjunction with more recent studies on transnational cultural industries and Asian pop culture trends (Jin, 2016; Lie, 2015).

Further analytical support is provided by the approaches to the study of youth subcultures and cultural resistance developed by Stuart Hall and members of the Birmingham School (Hall & Jefferson, 1976; Hall, 1997). However, in this study, they are interpreted through the lens of more recent research on digital communities and fan cultures (Jenkins, 2006; Duffett, 2013), which is particularly important in the context of social networks and media platforms.

Works on post-Soviet identity and nation-building in Kazakhstan and Central Asia are of significant importance to this study. Both earlier research (Schatz, 2004; Dave, 2007) and contemporary works analysing symbolic politics, cultural modernisation and national narrative are utilised here (Fauve, 2015; Kudaibergenova, 2017; Junisbai & Junisbai, 2019; Isaacs, 2018). This allows the Q-POP analysis to be embedded within a specific regional context, rather than being viewed solely as a derivative of global trends.

The empirical part of the study is based on a qualitative design and combines several complementary methods. Firstly, a discourse analysis was conducted of official statements, media publications and expert assessments concerning Q-POP. This approach allows us to identify not only the content of the statements, but also the broader ideological frameworks within which public discourse is shaped (Fairclough, 2013; Wodak & Meyer, 2016). In the Kazakhstani context, such methods have already been applied to the analysis of the media and national identity (Junisbai & Junisbai, 2019).

A qualitative content analysis was then carried out on music videos, song lyrics and visual imagery of key artists, including the band Ninety One. These materials were selected because visual-musical formats play a central role in the construction of meaning within pop culture. The analysis was based on the methodological principles of qualitative content analysis (Schreier, 2012; Krippendorff, 2018) and took into account contemporary research on visual culture and representation (Couldry, 2012; Kudaibergenova, 2017).

The categorical coding framework was developed based on theory and included linguistic representation, ethnocultural symbols, gender models, images of tradition and modernity, as well as social issues. This approach made it possible to systematically identify recurring elements and interpret them as stable cultural patterns, which is consistent with contemporary research practices in the cultural industries (Jin, 2016).

Particular attention was paid to the analysis of fan practices — primarily in the digital environment. User-generated content, online discussions and public actions were considered as forms of horizontal identity production. This approach is based on the theory of participatory culture (Jenkins, 2006) and its later interpretations in studies of digital communities (Duffett, 2013), as well as on regional studies of youth activism and media consumption (Junisbai & Junisbai, 2019). contributions to visual culture and representation A comparative analysis of Q-POP and K-POP was used not so much to identify direct borrowings as to identify mechanisms of cultural adaptation and localization. In this case, Q-POP is considered an example of the "translation" of a global cultural model into a local context, which is consistent with modern approaches to the study of cultural globalization. (Jin, 2016; Lie, 2015; Isaacs, 2018).

The data were interpreted using an interpretative approach incorporating elements of structural-functional analysis. The main focus was not on quantitative indicators, but on identifying semantic structures, symbolic strategies and the logic of their reproduction. Such a focus is characteristic of contemporary research on media and identity (Couldry, 2012).

The limitations of the study stem from its focus on the urban youth environment and the use of predominantly public sources. Furthermore, as noted in a number of works on Central Asia, empirical research into popular culture in the region still faces a lack of systematic data (Laruelle, 2015; Isaacs, 2018).

Thus, the chosen methodology allows us to view Q-POP not merely as a musical genre, but as a dynamic space of cultural interaction in which national identity is formed through a constant dialogue between global trends and local social and political contexts.

Discussion

In Central Asian countries, music is traditionally viewed not only as a form of artistic expression, but also as a key instrument in shaping national identity, collective memory and political attitudes. Particular attention is paid to the influence of Q-POP on young audiences. Research shows that this genre helps to strengthen cultural belonging and ethnic identity, whilst offering new forms of self-expression and social participation (Danabayev et al., 2021). Alongside this, elements of social reflection and critique are evident in the lyrics and visual imagery, reflecting the younger generation's attitude towards social and political processes (Zholamanova, 2021).

Novelty. Despite growing interest in Q-POP, the existing literature remains fragmented. Most studies focus on individual aspects—such as cultural globalisation, language policy or the influence of K-pop—and often employ simplified binary models of analysis (local/global, tradition/modernity). As a result, the complex dynamics of the interaction between cultural, political and media factors are only partially revealed.

This study proposes viewing Q-POP as a relational cultural space in which global cultural flows, national identity projects and media industries interact simultaneously. Unlike existing approaches, the focus is not on the opposition between these elements, but on their interconnection and mutual transformation.

The novelty of this work lies in the integration of cultural studies approaches, theories of globalisation and the analysis of post-Soviet identity to interpret Q-POP as a dynamic cultural practice. This allows for a fresh understanding of the role of popular music in shaping contemporary discourses of national identity in Kazakhstan and broadens the existing research framework.

Results

From Imitation to Creative Transformation: The Definition and Development of Kazakhstani Pop Music and Q-POP

Before analysing the evolution of Kazakhstani pop music and the Q-POP phenomenon, it seems necessary to clarify and conceptualise the very notion of Q-POP as used in this study. Unlike South Korean pop music (K-POP), whose name has an external origin and is linked to global branding, the term Q-POP was introduced at the same time as the debut of the Kazakhstani boy band Ninety One. Its emergence is directly linked to the activities of the production company JUZ Entertainment, which made no secret of the fact that the concept was formed on the basis of strategically borrowing elements from K-POP.

However, the company's founder, Yerbolat Bedelkhan (a former member of the Kazakhstani pop group Orda), ascribes a deeper national and cultural significance to the term Q-POP, emphasising the importance of the 'Q' component as a marker of Kazakh (Kazakhstani) identity. According to him, the creation of Q-POP was aimed at overcoming dependence on the Russian information space, which persisted even after the country gained state independence. He highlights the desire of the Turkic-speaking post-Soviet community to develop culture in their native language, pointing to a long period of cultural stagnation during the Soviet era (El kz, 2024).

According to Bedelkhan's interpretation, Q-POP is a musical genre aimed at a young audience and reflecting their values and social attitudes. Aesthetically, it is characterised by a synthesis of vocal and choreographic performances, the visual expressiveness of music videos, as well as the electronic and Western adaptation of the Kazakh language and individual elements of traditional musical culture. Q-POP is thus positioned as a tool for cultural modernisation and the re-imagining of national identity in the context of globalisation.

As Q-POP became institutionalised in Kazakhstan's public and official discourse, differences of interpretation arose regarding the boundaries of the term. Thus, the national news agency 'Kazinform' classifies as Q-POP performers who use the Kazakh language in contemporary popular music, including artists such as Dimash Kudaibergen. In this interpretation, Q-POP goes beyond the South Korean model of boy and girl groups and encompasses a wide range of genres — from hip-hop, rock and rap to R&B and lyrical pop. This expansive interpretation is supported by a number of Kazakhstani media outlets (Alexakis, 2018).

Furthermore, academic and media publications often adopt an approach in which Q-POP is viewed as a hybrid genre that blends Western pop music, rap, electronic dance music, R&B and elements of so-called 'Toi Music' performed in the Kazakh language.

Overall, it can be stated that in academic and media discourse, Q-POP is defined as a form of Western-oriented popular music, predominantly performed in the Kazakh language (with the possible use of Russian), and encompassing various genre forms — from idol groups to Kazakh-language rap, electronic music and R&B ballads. Thus, the contemporary understanding of Q-POP is considerably broader than the original model, which was based on emulating K-POP, and reflects processes of cultural adaptation and localisation of global musical trends within the context of national self-determination.

To gain a deeper understanding of the cultural significance of Q-POP, it is necessary to examine this phenomenon within the context of the historical evolution of popular music in Kazakhstan since independence. The emulation of Western and South Korean pop culture and its localisation did not begin in 2014; these processes have been developing since the early years of independence and can be broadly divided into several stages, with the years 2000 and 2015 marking key turning points.

In the early years of independence, a desire to reinterpret national identity through musical creativity took shape in major cities, particularly in Almaty. A characteristic example of this period is the band Urker (Kazakh: 'Үркеп' — 'constellation'), founded in 1994. Their artistic strategy lay in synthesising traditional Kazakh musical elements with Western arrangement techniques. The themes of their songs went beyond love lyrics to address issues of patriotism, historical memory and cultural revival. The celebration of Kazakhstan's independence was seen as a means of

reinforcing national consciousness. This approach was groundbreaking, as it signalled the ambition of local pop music to play a role in shaping national identity.

By the late 1990s, a domestic music industry had begun to take shape in the country. Independent television channels and radio stations began actively supporting young artists and broadcasting their music videos. At the same time, domestic male pop groups emerged, notably the band 'ABK' and other ensembles that paid particular attention to their stage image. Their repertoire included both musical interpretations of works by Kazakh poets and original lyrics created in collaboration with writers. Elements of traditional culture, such as the *dombra* or the image of the *aul*, were actively incorporated into the songs' imagery. Notable compositions include 'Nauryz', 'My Kazakhstan' and others. At the same time, a significant portion of the repertoire remained devoted to the theme of love. Musically, these works largely emulated folk and Russian pop music; at the same time, the use of traditional instruments was limited, and the performers' stage image was modernised and did not always emphasise ethnic specificity.

Whilst Kazakh-language music was 'rediscovering its roots', Russian-language pop music continued to dominate the market. It largely carried on the traditions of Soviet pop music whilst adapting to the new circumstances. For instance, the band A-Studio gained widespread popularity thanks to Russian-language hits such as 'Julia' and 'Soldier of Love', which focused primarily on personal and romantic experiences. Russian pop groups, including 'Laskovy Mai' and 'Na-Na', also retained significant influence, with their songs remaining popular among the Kazakhstani audience. Thus, during the first decade of independence, despite the state's political sovereignty, issues of national identity gradually receded into the background in popular culture, giving way to Western and Russian musical trends. The dominance of the Russian-language segment and the structural instability of the music industry, including the widespread distribution of pirated material, led to the demise of many bands that had emerged in the mid-to-late 1990s.

With the dawn of the 21st century, against a backdrop of the spread of the internet and the deepening of globalisation, Kazakhstani pop music entered a phase characterised by both genre diversity and a search for local identity. Since 2000, new musical genres have been actively developing in the country. A wave of hip-hop and R&B swept through the youth audience; artists and groups such as 'All-Davai' and 'Ghetto Dogs' emerged, followed later by Skriptonit, who took Kazakhstani hip-hop to a whole new level. His complex musical structures and original style contributed to the formation of a new cultural symbol for young people and secured his entry into the Russian market. It is noteworthy that, whilst performing songs predominantly in Russian, he emphasised that his music belonged to the Kazakhstani, rather than the Russian, cultural sphere (Stohler, 2021)

At the same time, many Kazakh performers, including Yerbolat Kudaibergen, were attempting to integrate elements of traditional musical culture into contemporary genres, including rap. In the track 'Men kazakpy' ('I am Kazakh'), energetic recitative is combined with the sound of the *dombra* and electronic arrangements. The repeated line "I am Kazakh, having died a thousand times and been reborn a thousand times" symbolically emphasises the value and historical complexity of the newly gained independence.

Thus, the development of Kazakhstani pop music in the post-Soviet period demonstrates a gradual transition from imitating external models to the search for and formation of its own cultural strategies, which subsequently laid the groundwork for the emergence of the Q-POP phenomenon as a new form of musical and identity-based self-expression (Rancier, 2014; Peyrouse, 2007)

On the other hand, although most Kazakhstani music groups of the late 1990s ceased to exist, the commercial foundation they had established contributed to the further institutionalisation of national music projects. Thus, with the participation of former members of the band ABK, the ethno-rock group Ulytau was formed (the name is borrowed from a sacred mountain in Kazakh

history), which attracted attention both in Kazakhstan and beyond thanks to its synthesis of traditional Kazakh instruments with rock music. At the same time, a 'second wave' of boy bands began to emerge, including groups such as 'Zhigitter', Orda, 'Ringo' and others. Most of them performed songs in the Kazakh language and modelled themselves on South Korean idol groups, paying particular attention to choreography and stage image, thereby laying the foundations for the subsequent development of the pop idol industry. At the same time, the first Kazakhstani girl groups appeared on the scene, notably 'Rakhat-Lukum' and 'Serdtsyedki'.

With the development of internet technologies and the gradual modernisation of the music industry, increasing importance has been attached to the visual aspect of musical productions. The production of music videos has evolved into a distinct medium of artistic expression, with the visual imagery increasingly tailored to the specific genre of the work. Thus, in the music video for Batyrkhan Shukenov's patriotic ballad 'Otan Ana' ('Motherland'), the singer, against a backdrop of steppe landscapes, extols the traditional values of the Kazakh people; the frame successively features a yurt, a dombra, kumys, clarified butter and other elements of ethno-cultural symbolism. The image of the performer, stylised as an akyn singing in the steppe, creates an atmosphere of solemnity and sacredness. Such an 'ethnographic' visual strategy was characteristic of several patriotic music videos from this period, including projects by groups such as ABK.

At the same time, the music videos of Kazakhstani rap artists and boy bands - particularly Orda - were dominated by a different aesthetic: one that was distinctly modern and urban. The performers, dressed in contemporary clothing, dance and unfold storylines centred on the emotional experiences of young city dwellers; in some cases, elements of fantasy or crime fiction are used. Even in the patriotic songs of rap artists, the focus shifts from traditional folklore to historical and modernisation themes. Thus, in the music video 'Men kazakpy' ('I Am Kazakh'), a significant portion of the visual material consists of archive footage from the Soviet era, scenes of industrial construction, and images of historical figures (including Yuri Gagarin, associated with the Baikonur Cosmodrome). The juxtaposition of Soviet and post-independence achievements, including sporting victories, creates a narrative of continuous progress and emphasises the modernist aspirations of Kazakhstani society.

Overall, between 2000 and 2014, Kazakh-language popular music was characterised by increasing genre diversification. The thematic range broadened: whereas love songs had previously dominated, a balance between romantic and patriotic themes subsequently emerged. The growing popularity of Kazakh female performers and the sustained commercial success of Kazakh-language projects signalled the formation of an independent market and the gradual institutionalisation of the industry. Artists who had achieved recognition by adopting Western and Korean production and stylistic models began to actively use these mechanisms to promote new performers.

Thus, the evolution of Kazakh-language pop music during the period under consideration created the structural, aesthetic and institutional conditions for the emergence of Q-POP as an independent genre, combining elements of global pop culture with local forms of cultural representation.

In 2015, Kazakhstan's music scene underwent a significant and, in many ways, revolutionary shift, marked by the emergence and rapid rise of the Q-POP phenomenon. This was not merely the emergence of a new genre of popular music, but the formation of a large-scale cultural and social movement that spread both within the country and beyond its borders. Q-POP succeeded in adapting global forms of pop culture to the national context, becoming a vehicle for articulating a new model of ethno-cultural identity for the post-Soviet generation of Kazakhstani youth.

The emergence of Q-POP was driven by a combination of socio-political, cultural and technological factors. In the 2010s, processes of symbolic 'derussification' and the institutional strengthening of Kazakh national identity intensified in Kazakhstan. A landmark step was the 2017

announcement of the transition of the Kazakh alphabet from Cyrillic to the Latin script. In this context, the prefix 'Q' acquired a particular ideological significance, becoming established in some state and branding designations (Qazaqstan, Qazaq Air) as a symbol of a renewed, modernised national identity. It was within this political and cultural environment that the conditions for the emergence of Q-POP were formed.

From the perspective of the music industry, by the early 2010s, the Kazakhstani market was structurally divided between Russian-language pop music and the more traditionally oriented Kazakh-language pop scene. At the same time, young people were actively drawn to Western pop culture and the global phenomenon of K-POP. The development of the local industry in the 2000s and the investment activity of producers helped create a demand for a product capable of synthesising modern aesthetic standards with the national cultural code. A key role was played by producer Yerbolat Bedelkhan (a former member of the group 'Orda'), who founded the company Juz Entertainment in 2014 and was the first to systematically introduce the Korean model of idol training in Kazakhstan. Trainees were selected and trained through the television project 'K-top idols', and on 1 September 2015, the male group Ninety One made its debut; the name refers to 1991 – the year of Kazakhstan's independence. Rapper Yerbolat Kudaibergen, who collaborated in particular with Dimash Kudaibergen, also provided significant support to the young performers. Thus, the new generation of Q-POP was initially built upon the achievements of the previous stage in the development of Kazakh-language pop music.

In terms of visual and performative aesthetics, Ninety One has radically transformed perceptions of what constitutes an acceptable image for a Kazakhstani artist. Bright hair colours, stage make-up, statement accessories and a style borrowed from the K-pop industry clashed with the gender and cultural norms dominant in a conservative society (Oryn, 2018). The group faced criticism from representatives of the traditional music scene, who accused them of imitating Korea and 'failing to align' with national values; during the first tour, nine out of sixteen concerts were cancelled due to public pressure (Yoon, 2020). However, it was precisely the controversy and the cultural 'shock' that brought the group nationwide fame. The production company swiftly devised a media strategy, including the creation of documentary videos about the difficulties the group faced in establishing itself. Success abroad, including the single 'Qaytadan' ('Again') reaching number one on the Turkish music channel TMB, contributed to the institutional recognition of Q-POP (cn.inform.kz, 2016). At the same time, the international success of Dimash Kudaibergen (in particular, following his participation in the Chinese TV show 'Singer' in 2017) confirmed the importance of professional image management in promoting national music. The Gakku television channel has gradually become a key platform for promoting the new pop scene. Following Ninety One's debut, JY Entertainment initiated the formation of new male and female groups (Black Dial, Newton, Mad Men, Ziruza, etc.), whilst Ninety One's appearances on South Korean TV shows contributed to the project's further internationalisation. Thus, by the end of the 2010s, a stable Q-POP ecosystem had formed as an independent cultural phenomenon.

In parallel with the development of idol culture in Kazakhstan, the position of rap was strengthening. In contrast to the androgynous aesthetics of Q-POP, the rap scene retained more traditional models of masculinity. The Kazakhstani rap scene significantly outnumbered idol groups and was characterised by internal stylistic and ideological diversity. Some performers (for example, Shiza) portrayed images associated with criminal themes, violence, and an emphasised 'southern' identity (Koch & White, 2016). The self-deprecating label 'manbet' ('provincial') became widespread, through which artists criticised urbanised Kazakhs for losing their 'authenticity'. Vloggers also played a significant role in the genre's development, particularly the bilingual collective Irina Kairatovna (IK), which began as a comedy project and later transitioned to a musical format. The group actively used satire to explore social realities and Kazakh-Russian relations; in 2019, it declined support from the pro-government Salem Foundation.

The political changes of 2019, linked to the resignation of Nursultan Nazarbayev, galvanised the protest potential of the rap scene (Kudaibergenova, 2020; Junisbai & Junisbai, 2019). Several artists openly criticised the mechanism of the transfer of power and socio-economic inequality. Opposition movements, such as Oyan Kazakhstan, also emerged during this period. Although these protest initiatives soon failed, the ensuing COVID-19 pandemic and persistent social inequality in Kazakhstan led Q-POP artists to begin actively and sharply criticising the government between 2020 and 2022 (Kudaibergen, 2024). In the song 'Taboo' (2020), recorded jointly by IK and Ninety One, direct criticisms were levelled at state censorship, corruption and the devaluation of the national currency, including satirical allusions to the ruling authorities. In the track '5000' (2021), IK explored the theme of everyday corruption, metaphorically portraying petty bribery as a systemic phenomenon; the music video criticised specific infrastructure projects and symbolic political gestures. The song went viral online: by the end of 2021, it had racked up 29 million views on YouTube, a figure exceeding the country's population. The members' interviews with the Russian media were accompanied by harsh criticism of social stratification and corruption, whilst simultaneously declaring a positive patriotic attitude towards Kazakhstan, its historical heritage, and potential for development.

Thus, the period after 2015 is characterised by the institutionalisation of Q-POP as a new form of cultural self-identification, combining global aesthetic models with local content. At the same time, the rap scene has become an important channel for articulating socio-political criticism. Taken together, these processes testify to the transformation of Kazakhstani popular music into a significant instrument for shaping national discourse, modernising identity, and fostering public reflection.

The wave of critical songs effectively came to an end with the events of January 2022. Large-scale social unrest forced the Kazakhstani authorities to tighten their control over the cultural sphere at an early stage. Although internationally renowned groups such as IK, as well as certain popular boy bands, generally avoided direct sanctions, many rap artists and members of male groups who publicly supported or were involved in the January events were subsequently prosecuted and convicted.

At the same time, the 'New Kazakhstan' agenda that followed the crisis implied a certain degree of liberalisation and the acceptance of moderate critical rhetoric in the music sector. However, a significant proportion of rap artists chose to adopt a compromise stance, aligning their work with the official reformist discourse. A telling example was the track 'Kok tu' ('Blue Flag'), released in June 2022 by the group IK in collaboration with a number of Kazakhstani rap artists. In it, the artists called for honesty and the consolidation of society above ethnic, religious, and tribal differences, which largely echoed the rhetoric of K.-Z. Tokayev's political reforms. Although elements of criticism directed at state propaganda remained, the tone of the track became noticeably more moderate compared to the previous phase.

At the same time, this period saw a decline in the popularity of Kazakhstani boy bands. This was due, on the one hand, to the economic difficulties faced by production companies (in particular, Juz Entertainment) during the pandemic, and on the other, to a lack of strategic planning regarding the artists' long-term career paths. In 2022–2023, a number of well-known groups, including Ninety One, terminated their contracts with production centres and moved towards self-management or setting up their own studios. After 2021, one of the most popular new groups – ALPHA – also left Juz Entertainment and adopted an autonomous operating model. The group, consisting of members born in the 2000s, is even more consistently oriented towards the Korean idol model: in style, stage image, and strategy for active engagement with fan communities. At the same time, the group strives to emphasise its international openness. In response to criticism of 'disrespect for tradition', the members typically respond via social media,

posting performances of songs in Kazakh or showcasing their participation in events related to rural and nomadic culture.

Overall, the development of Q-POP reflects a dual logic. On the one hand, this phenomenon has continued trends already emerging in Kazakh-language pop music (the strengthening of the role of the Kazakh language, an emphasis on individualised self-presentation, and the high importance of visual elements). On the other hand, Q-POP was initially based on successful international industry models, primarily the Korean one. However, it subsequently moved beyond mere formal borrowing, integrating the Kazakh language, traditional cultural values and the contemporary youth agenda into a unified system of symbolic codes. In doing so, Q-POP has transformed into a significant instrument of cultural and political articulation and representation of a new Kazakhstani identity.

Co-optation within the official narrative: Q-POP as an instrument of state 'soft power'

As the influence of Q-POP grows among Kazakhstan's younger generation, state bodies are paying increasing attention to this cultural phenomenon and becoming involved in the process of its institutionalisation. Within the specific political and cultural context of Kazakhstan, the authorities are seeking to integrate Q-POP into the national narrative, viewing it as a tool for showcasing the country's modern image and strengthening cultural confidence. This process of co-optation, however, is not limited to direct assimilation or strict administrative control; it constitutes a complex system of interactions and negotiations between the state and cultural producers, reflecting the mechanisms through which official nationalism exerts a guiding and disciplining influence on youth culture.

One of the first manifestations of Q-POP's incorporation was its inclusion in official cultural events. In recent years, an increasing number of Q-POP groups have been invited to participate in state holidays and festivals, including City Day in Nur-Sultan, the celebration of Kazakhstan's Independence Day, and other public events of national significance. In such contexts, the groups' stage imagery and repertoire are often adapted to align with the dominant state discourse: the visual representation of ethno-cultural symbols is emphasised, song lyrics highlight themes of national unity and social harmony, and performance practices are aligned with mainstream aesthetic expectations.

Another telling sign is the inclusion of individual members of influential groups, such as Ninety One and IK, within state youth organisations. This creates a channel for institutional integration through which Q-POP is gradually incorporated into the framework of official cultural policy and used to construct the image of 'New Kazakhstan'.

The second dimension of co-optation relates to the use of Q-POP as a tool for external cultural representation. As the genre's audience expanded, it began to be viewed as a vehicle for 'soft power' and an element of cultural diplomacy. Kazakhstan's Ministries of Foreign Affairs and Culture promoted Q-POP groups within the framework of international cultural exchanges, positioning them as symbols of a young, open and modernising society.

Official recognition, on the one hand, helped to strengthen the genre's status and expand its institutional capabilities; on the other, it created a context of normative expectations, exerting an indirect influence on the thematic and ideological content of musical production.

The process of co-optation is evident not only in institutional practice but also in the transformation of the official discourse on Q-POP. In their publications, state and state-affiliated media emphasise the genre's connection to Kazakh cultural tradition, highlighting its contribution to the development of the creative economy and the promotion of the national language, whilst simultaneously downplaying its original subcultural and protest potential. Media narratives pay particular attention to how artists draw inspiration from traditional music, represent Kazakh culture on the international stage, and encourage members of other ethnic groups to learn the Kazakh language.

At the same time, the authorities' attitude towards more radical forms of criticism remains ambivalent. With regard to groups and performers who openly criticise the government and political leadership, officials publicly acknowledge the right to freedom of expression and interpret the presence of criticism as evidence of reforms and the expansion of freedom of speech. However, in cases where statements go beyond what is acceptable in terms of prevailing social values, punitive measures are applied. For instance, in the summer of 2022, the rapper Shiza was brought before the administrative courts following an incident at a music festival where, whilst under the influence of alcohol, he desecrated the national flag. This incident catalyzed intensifying a public campaign to promote norms governing respect for state symbols.

The attitude of the Q-POP creators themselves towards the process of official integration is characterised by an inherent contradiction. On the one hand, state recognition opens up access to resources, broadens the audience, ensures participation in prestigious events, and helps to remove the stigma of being a 'subculture' or a 'marginal phenomenon'. For some artists—particularly those who were originally focused on promoting the Kazakh language—cooperation with state bodies becomes a means of achieving their own cultural goals, which objectively encourages them to align with the official agenda.

On the other hand, institutional support comes with certain forms of cultural regulation. The demands to conform to mainstream norms and socially approved values may weaken the genre's original innovative and protest potential, distancing it from its subcultural roots.

The case of Q-POP illustrates a broader structural paradox characteristic of post-Soviet nation-building processes. On the one hand, the state requires modern cultural forms and innovative symbols that enable it to demonstrate dynamism, openness and global competitiveness. On the other, it must maintain stable traditional markers of identity that ensure the continuity and legitimacy of the national project.

Q-POP finds itself at the centre of this tension: it is simultaneously modernist and traditionalist, globally oriented and locally rooted. It is precisely this hybridity (Kraidy, 2005) that makes it an attractive resource for official nationalism, which seeks to harness the genre's potential to strengthen national identity whilst simultaneously guiding and regulating its development.

Against the backdrop of the ongoing transformation of Kazakhstan's cultural landscape, Q-POP, as a new form of cultural practice, demonstrates that the state's co-optation of this movement reflects its desire to integrate diverse cultural resources into a project aimed at strengthening national identity. However, this integration is never exhaustive: Q-POP retains a certain degree of autonomy and potential for resistance.

Youth culture of resistance: Q-POP as a generational manifesto

While the official incorporation of Q-POP indicates the state's attempt to guide and utilise youth culture, its popularity among young people reveals another aspect—the function of generational expression. Amid the rapid social transformation of Kazakhstani society, Q-POP has become an important platform for the younger generation's self-reflection, the re-evaluation of social norms and the formation of subcultural identity.

This resistance does not take the form of direct political confrontation. It manifests itself through the creation of new symbols, aesthetic innovations and the formation of communities within which everyday cultural practices become a space for re-examining and renegotiating established norms.

One of the key areas of this symbolic challenge has been the rethinking of traditional gender norms. In Kazakhstani society, where traditional social structures coexist with modernist lifestyles, issues of gender roles and masculinity remain a source of intergenerational tension.

Q-POP groups, foremost among them the genre's pioneers Ninety One, have challenged traditional notions of 'masculinity' through androgynous aesthetics, experimental fashion, and

hybrid stage performance. This visual transgression provoked a sharp reaction from conservative circles, where such practices were interpreted as a violation of tradition and cultural norms.

At the same time, this strategy does not imply a radical break with cultural heritage. Rather, it involves seeking a new creative space between tradition and modernity. In some music videos, elements of national costume are not rejected, but are modernised and subjected to stylistic deconstruction. In this way, a model of gender representation is formed that simultaneously acknowledges tradition and frees itself from its normative rigidity. This strategy of negotiation allows for the preservation of cultural continuity, creating new opportunities for young people's identity practices (Oryn, 2018).

Another significant dimension of cultural resistance is Q-POP's involvement in language policy. Following independence, the language issue became a central element of nation-building. Constitutional provisions established Kazakh as the state language, whilst recognising the special status of Russian in the sphere of inter-ethnic communication.

Within this complex sociolinguistic context, Q-POP has developed a strategy of hybrid multilingualism: a single composition may combine Kazakh, Russian, and English. This practice carries significant cultural and political implications.

On the one hand, it helps to elevate the symbolic status of the Kazakh language within popular culture, thereby aligning with the state's policy of promoting it. On the other hand, the retention of Russian and English reflects an acknowledgement of a multilingual social reality and the global cultural sphere.

The result is the formation of an inclusive model of youth identity that transcends rigid ethnic boundaries and creates a space for cultural solidarity based on shared aesthetic preferences.

Q-POP's subversive potential is also evident in the practices of fan communities. For example, the Ninety One fan club 'Eagle Z.' demonstrates a high degree of self-organisation and public visibility. Fans do not limit themselves to passive consumption of the musical product; they actively participate in the construction of meaning through social media, offline events and collective acts of support. Such participation forms a relatively autonomous cultural space in which young people can construct alternative models of identity and values, distinct from official discourses and traditional media narratives (Otan, 2018).

The inter-ethnic nature of these communities deserves particular attention. The fanbase includes representatives of various ethnic groups — Kazakhs, Russians and other minorities. This structure partially transforms the traditional model of identity politics based on ethnic boundaries, offering a form of solidarity grounded in cultural taste and shared symbolic references.

In music videos and rap projects, national symbolism is increasingly interpreted not only through traditional folkloric elements, but also through social issues common to young people—corruption, social inequality, and complex historical and political themes. Such artistic choices create new foundations for collective memory and solidarity that go beyond the confines of a narrowly ethnic narrative (Zholamanova & Oh Chong Jin, 2024)

At the same time, Q-POP's cultural resistance is not without its internal limitations. Commercial success and gradual mainstreaming inevitably lead to a partial loss of its original protest potential and its adaptation to market logic and official discourse.

Furthermore, within the genre itself, there remains a tension between tradition and modernity, the local and the global, commercialisation and artistic autonomy.

These contradictions reflect the broader experience of young people in Kazakhstan, who are faced with the need to choose between different models of identity and social behaviour.

To summarise the above, it can be said that Q-POP, as a form of youth cultural practice, does not represent a direct challenge to the existing order, but rather a space of symbolic autonomy. Through the production of new aesthetic forms and the development of online communities, it

creates a relatively safe zone for the younger generation to experiment with identity and social roles.

The tension between ‘top-down’ processes—co-optation and institutionalisation—and ‘bottom-up’ initiatives—cultural innovation and subcultural self-organisation—forms the core of Q-POP’s cultural-political dynamics. It is within this field of interaction that its unique position in contemporary Kazakhstani society is formed.

Thus, Q-POP is not merely a musical genre, but also a key indicator of the transformation of national identity, a mechanism for rethinking traditional norms, and a laboratory for new cultural possibilities in post-Soviet Kazakhstan.

Negotiations in a climate of confrontation: between co-optation and resistance

The trajectory of Q-POP’s development in Kazakhstani society cannot be reduced to either a simple ‘top-down’ model—institutional co-optation—or a purely ‘bottom-up’ one—subcultural resistance. It is a multi-level and multi-actor process of constant interaction and rivalry, involving state structures, market mechanisms, defenders of traditional culture and young creators. The result is a dynamic and complex mechanism of cultural negotiation. Understanding the nature, logic and consequences of this process is key to interpreting the social significance of Q-POP.

One side of this conflict is represented by conservative forces and advocates of ‘cultural purity’. Since the emergence of Q-POP, and particularly following the appearance of its leading groups (notably Ninety One) on national television, there has been a strong backlash from traditionalist circles. Criticism has centred on several aspects: accusations of imitating K-POP as a rejection of authentic tradition; claims that traditional values are being undermined through appearance and stage aesthetics; and suspicions that commercial success is prioritised over artistic sincerity.

Such assessments came not only from the general public but also, in part, from cultural administrators, reflecting a broader cultural anxiety linked to globalisation. It is noteworthy that the criticism often concerned primarily external form rather than content. Criticisms that the performers ‘did not look like Kazakh men’ focused on visual style or the use of instruments, rather than on the degree of ‘Kazakhness’ in the music itself. This testifies to the normative narrowness of conceptions of national culture, limited primarily to folkloric and ethnographic markers (Otan, 2019). Nevertheless, such discursive practices shape the symbolic environment in which Q-POP develops and influence the official policy regarding its positioning and support.

In response to pressure from conservative circles and attempts at institutional integration, the creators of Q-POP have demonstrated a high degree of adaptability. This adaptability manifests itself in several ways.

Firstly, musically speaking, there is a gradual deepening of their engagement with traditional material: from the superficial use of ethnic symbols to a more complex form of cultural synthesis, involving the reworking of aesthetic principles, a return to classical literary motifs, and the creative transformation of philosophical ideas.

Secondly, the artists adopt a differentiated public strategy: in official contexts, they emphasise continuity and cultural heritage, whilst in youth communities they maintain an innovative and partly protest-oriented image.

Thirdly, in the commercial sphere, they use the effect of public controversy to expand their audience, whilst simultaneously raising the artistic quality of their product to legitimise themselves not only as a media project but also as a cultural phenomenon.

A typical example of this evolution is the changing approach to national symbolism. Whereas in the early stages, traditional elements were displayed in an explicit and visually emphasised form (national costumes, ethnic instruments), integration subsequently became more conceptual: tradition is interpreted through a contemporary formal language, creating a hybrid cultural model that transcends the binary opposition of ‘East–West’.

The commercial market plays a dual role in this field of conflict. On the one hand, it affords Q-POP relative autonomy from direct ideological control, allowing it to cater to the tastes of a young audience. On the other hand, the demands of commercial viability can undermine the genre's original innovative and critical potential, contributing to its gradual normalisation.

Nevertheless, cultural producers are not merely passive subjects of market logic. On the contrary, there are attempts to strike a balance between commercial success and artistic experimentation, thereby establishing a model for the coexistence of cultural innovation and market sustainability.

Of particular significance is the correlation between the development of Q-POP and the transformation of Kazakhstan's national policy. Since gaining independence, the state strategy has gone through several stages: from emphasising the ethno-cultural dominance of the titular nation to proclaiming cultural diversity, and then to the formation of a civic model of national identity.

The evolution of Q-POP shows a subtle correlation with these changes. During the phase of strengthening the Kazakh ethno-cultural component, the emphasis on the Kazakh language and traditional symbols resonated with the state agenda. During the period when cultural pluralism was being promoted, the genre's multilingual practice and inter-ethnic appeal were in line with the official stance. In the context of the formation of civic identity, Q-POP, as a supra-ethnic youth culture, proved to be in tune with the idea of an inclusive national community.

The Q-POP case demonstrates the complex interplay between cultural innovation and social structure in post-Soviet society. Social institutions set the boundaries of what is permissible and delineate the space of possibilities; however, cultural practices, through symbolic production, are capable of gradually expanding and redefining these boundaries. It is precisely this dialectical dynamic that ensures the gradual transformation of society whilst preserving elements of continuity.

The field of cultural dialogue in which Q-POP operates remains open and fluid. The development of digital media and the acceleration of global cultural flows are creating new opportunities for international dialogue and regional cooperation — particularly within Central Asia, Mongolia and in engagement with the Korean music industry. At the same time, changes in the political and economic climate and a complex geopolitical landscape may introduce new constraints. Regardless of specific trajectories of development, Q-POP retains its significance as a unique cultural arena of confrontation and negotiation. Its analysis provides a valuable analytical tool for understanding the processes of cultural and identity transformation in post-Soviet Kazakhstan.

Basic Provisions

The study developed and formulated the following scientific results:

- It was revealed that Q-POP was formed under the influence of globalization, digitalization, and the Korean pop industry, while adapting national cultural elements of Kazakhstan.
- It was established that Q-POP represents an example of cultural glocalization, combining global musical formats with the Kazakh language, local symbolism, and national identity.
- It was revealed that Q-POP has become an important space for the formation of modern youth identity and cultural expression in Kazakhstan.
- It was found that the genre has sparked public debates related to issues of traditional values, gender aesthetics, and the cultural influence of global popular culture.
- It was established that, with the institutionalization and commercialization of Q-POP, it gradually integrated into the official cultural discourse and national branding of Kazakhstan.
- It was determined that Q-POP has the potential as a tool of soft power and cultural diplomacy, contributing to the promotion of Kazakhstan's modern image in the digital media

space. - The existence of internal contradictions within Q-POP between globalization and local identity, commercialization and cultural resistance is demonstrated.

Conclusion

A comprehensive analysis of the Q-POP phenomenon allows us to clarify the internal dynamics of cultural processes in Kazakhstan and to rethink the specifics of post-Soviet nation-building. The formation of national identity is seen not as a unilateral state project, but as a multi-level process of cultural negotiation involving various actors and internal tensions.

State institutions seek to integrate Q-POP into the official narrative and use it as a resource for symbolic representation; conservative forces criticise the genre on grounds of 'authenticity'; the market directs its development according to the logic of commercial efficiency; young people view it as a space for exploring and articulating new identities. The interaction of these forces creates a dynamic equilibrium: Q-POP remains within the mainstream whilst retaining the potential for cultural innovation and elements of symbolic opposition. In doing so, it reflects the unfinished and open-ended nature of Kazakhstan's national project.

The Q-POP case challenges simplistic interpretations of globalisation. It cannot be reduced to either cultural homogenisation or direct local resistance. The genre demonstrates a mechanism of glocalisation: borrowed K-POP models are integrated with Kazakh traditions and current social realities, forming hybrid forms that are both globally recognisable and locally specific. Cultural innovation arises here as a result of creative adaptation, rather than mechanical copying.

From an intergenerational perspective, Q-POP reflects the cultural agency of Kazakhstan's youth amidst the rapid social changes and normative uncertainty of the post-Soviet era. Rather than passively adopting external models, the younger generation engages in independent cultural construction. Q-POP serves both as a result and an instrument of this process, providing symbolic resources for the formation of identity and a sense of 'ontological security'.

The study has limitations. Q-POP remains a relatively recent phenomenon, and its long-term effects require further empirical analysis. The focus on an urban student audience narrows the picture of how the genre is perceived in rural and other social contexts. Furthermore, a more in-depth study of trans-ethnic practices and intercultural reception appears to be a promising avenue for further research.

Thus, Q-POP extends beyond the entertainment industry and serves as an analytical lens through which to view post-Soviet transformation. It provides a space for cultural discourse on the substance of national identity and stands as a testament to the creativity of the younger generation in the context of globalisation. At the intersection of local and global influences, Q-POP remains a key indicator and interpretative resource for analysing the cultural dynamics of contemporary Kazakhstan.

Authors contribution:

Nurzhayeva Alina Maratovna – gathering information, literature review, data analysis, and manuscript writing.

Orazgali Gulzha - methodology development, data collection, interpretation of results, and editing of the manuscript.

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