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Philological Sciences

Fransız və Azərbaycan dillərində frazeoloji birləşmələrin tərcümə üsulları

Rəfiyeva Xuraman Əli qızı

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Xülasə

Məqalədə fransız və Azərbaycan dillərində frazeoloji birləşmələrin linqvistik xüsusiyyətləri, onların milli-mədəni məzmunu və tərcümə zamanı meydana çıxan əsas problemlər araşdırılmışdır. Frazeoloji vahidlər dilin obrazlılığını, xalqın dünyagörüşünü, tarixi təcrübəsini və mədəni dəyərlərini əks etdirən mühüm dil vasitələridir. Bu səbəbdən onların tərcüməsi yalnız leksik uyğunluğun tapılması ilə məhdudlaşmır, həm də semantik, üslubi və pragmatik xüsusiyyətlərin qorunmasını tələb edir. Məqalədə tam ekvivalent, qismən ekvivalent, funksional analoq, təsviri tərcümə, kalka və transformasiya üsulları elmi baxımdan təhlil edilmiş, fransız və Azərbaycan dillərindən seçilmiş nümunələr əsasında müqayisəli izah verilmişdir. Tədqiqat nəticəsində müəyyən edilmişdir ki, frazeoloji birləşmələrin uğurlu tərcüməsi üçün yalnız dil bilikləri deyil, həm də hər iki xalqın mədəniyyəti, adət-ənənələri və ünsiyyət xüsusiyyətləri haqqında dərin bilik tələb olunur.

Açar sözlər: frazeologiya, frazeoloji birləşmə, tərcümə, fransız dili, Azərbaycan dili, ekvivalentlik, funksional analoq.

Giriş

Qloballaşma şəraitində müxtəlif dillər arasında qarşılıqlı əlaqələrin genişlənməsi tərcümə fəaliyyətinin əhəmiyyətini daha da artırmışdır. Xüsusilə bədii, publisistik və elmi mətnlərin tərcüməsində frazeoloji birləşmələrin düzgün ifadə olunması tərcümənin keyfiyyətini müəyyən edən əsas amillərdən biridir. Frazeoloji vahidlər dilin ən sabit və milli xüsusiyyətləri özündə cəmləşdirən elementlərindən hesab olunur. Onlar xalqın düşüncə tərzini, həyat tərzini, məişətini və tarixi inkişafını əks etdirərək dilin emosional-ekspressiv imkanlarını zənginləşdirir.

Fransız və Azərbaycan dilləri müxtəlif dil ailələrinə mənsub olsalar da, hər iki dildə zəngin frazeoloji sistem mövcuddur. Bu frazeoloji sistemlərdə həm ümumbəşəri məzmun daşıyan, həm də yalnız müəyyən xalqın mədəniyyətini əks etdirən ifadələrə rast gəlinir. Buna görə də onların tərcüməsi zamanı yalnız sözlərin lüğəvi mənasına əsaslanmaq kifayət etmir. Tərcüməçi frazeoloji vahidin semantik yükünü, emosional çalarını, üslubi funksiyasını və milli-mədəni xüsusiyyətlərini də nəzərə almalıdır.

Frazeoloji birləşmələrin tərcüməsi müasir tərcüməşünaslığın mürəkkəb problemlərindən biri hesab edilir. Çünki bir çox hallarda mənbə dildə işlənən ifadənin hədəf dildə tam qarşılığı olmur. Belə hallarda müxtəlif tərcümə üsullarından istifadə edilir. Tərcüməçinin əsas məqsədi yalnız informasiyanı deyil, həm də ifadənin emosional təsirini və üslubi dəyərini qorumaqdır.

Frazeologiya dilçiliyin mühüm sahələrindən biri kimi sabit söz birləşmələrinin yaranma qanunauyğunluqlarını, semantik quruluşunu, funksional xüsusiyyətlərini və işlənmə imkanlarını öyrənir. Frazeoloji vahidlər sərbəst söz birləşmələrindən fərqli olaraq bütöv məna ifadə edir və onların ümumi mənası ayrı-ayrı komponentlərin lüğəvi mənalарının cəmi ilə müəyyən olunmur. Məhz bu xüsusiyyət onların tərcüməsini çətinləşdirən əsas amillərdəndir.

Fransız dilində işlənən *donner sa langue au chat, tourner autour du pot, avoir le cœur sur la main, chercher midi à quatorze heures* kimi ifadələr yalnız sözbəsöz tərcümə olunduqda mənasını itirir. Azərbaycan dilində də "başını itirmək", "ürəyi yumşaq olmaq", "sözü dolandırmaq", "əlini üzmək",

"dağdan ağır olmaq" kimi frazeoloji vahidlər eyni xüsusiyyətə malikdir. Buna görə də tərcümə prosesində onların funksional və semantik ekvivalentlərinin müəyyən edilməsi xüsusi əhəmiyyət daşıyır.

Müasir tərcümə nəzəriyyəsində qəbul olunur ki, frazeoloji vahidlərin tərcüməsində əsas məqsəd forma oxşarlığını deyil, məna və funksional ekvivalentliyi qorumaqdır. Bu baxımdan fransız və Azərbaycan dillərinin frazeoloji sistemlərinin müqayisəli şəkildə öyrənilməsi həm nəzəri, həm də praktik əhəmiyyət daşıyır. Belə tədqiqatlar iki dil arasında tərcümə keyfiyyətinin yüksəldilməsinə, linqvokulturoloji xüsusiyyətlərin daha düzgün çatdırılmasına və peşəkar tərcüməçilərin hazırlanmasına mühüm töhfə verir.

Frazeoloji vahidlərin tərcüməsi tərcüməşünaslığın ən mürəkkəb sahələrindən biri hesab olunur. Bunun əsas səbəbi həmin vahidlərin yalnız dil faktı deyil, həm də xalqın tarixi, məişəti, adət-ənənələri, milli psixologiyası və mədəni dəyərləri ilə sıx bağlı olmasıdır. Frazeoloji birləşmələrin böyük əksəriyyəti məcazi məna daşdığı üçün onların sözbəsöz tərcüməsi əksər hallarda məna itkisinin yaranmasına səbəb olur. Buna görə də tərcüməçi yalnız dil biliklərinə deyil, həm də mənbə və hədəf dillərin mədəni xüsusiyyətlərinə dərinlən bələd olmalıdır.

Fransız və Azərbaycan dillərinin frazeoloji sistemi zənginliyi və ifadəliliyi ilə seçilir. Hər iki dildə insan xarakterini, davranışını, hiss və emosiyalarını, əmək fəaliyyətini və gündəlik həyatı əks etdirən yüzrlə sabit ifadə mövcuddur. Lakin bu ifadələrin forması və semantik quruluşu həmişə üst-üstə düşmür. Buna görə də tərcümə zamanı müxtəlif üsullardan istifadə edilir. Frazeoloji vahidin həm məna, həm də üslubi baxımdan hədəf dildə tam qarşılığı mövcud olduqda tam ekvivalent üsulundan istifadə edilir. Bu üsul ən uğurlu tərcümə üsulu hesab olunur, çünki ifadənin semantik yükü və emosional təsiri qorunub saxlanılır. Tam ekvivalentlə tərcümə isə belə alınır:

Məsələn, fransız dilində **avoir le cœur sur la main** ifadəsi səxavətli, xeyirxah və əliaçıq insan haqqında işlədilir. Azərbaycan dilində bunun ən uyğun qarşılığı **"əli açıq olmaq"** frazeoloji vahidir. Hər iki ifadə eyni məna yükünü daşıyır və oxucuda oxşar emosional təsir yaradır.

Digər nümunə kimi **verser des larmes de crocodile** ifadəsini göstərmək olar. Bu ifadə Azərbaycan dilində işlənən **"timsah göz yaşları tökmək"** frazeoloji vahidi ilə tam uyğun gəlir. Hər iki dildə bu ifadə qeyri-səmimi peşmançılığı və ya saxta mərhəməti bildirir.

Tam ekvivalentdən istifadə tərcümənin təbiiyyətini artırır və müəllifin üslubunu qorumağa imkan verir. Lakin müxtəlif dillərin milli xüsusiyyətləri səbəbindən belə uyğunluqlara hər zaman rast gəlinmir.

Frazeoloji vahidin tam qarşılığı olmadıqda, lakin eyni məzmunu ifadə edən yaxın ifadə mövcud olduqda qismən ekvivalent üsulundan istifadə edilir. Bu halda forma dəyişsə də, əsas semantik məzmun saxlanılır.

Fransız dilində **tourner autour du pot** ifadəsi danışarkən əsas fikri deməmək, sözü uzatmaq mənasında işlədilir. Azərbaycan dilində buna ən yaxın qarşılıq **"sözü dolandırmaq"** ifadəsidir. Burada obraz fərqli olsa da, məna və kommunikativ funksiya eynidir.

Başqa bir nümunə **mettre de l'eau dans son vin** ifadəsidir. Sözbəsöz tərcümədə "şərabına su qatmaq" mənasını verir. Lakin frazeoloji baxımdan insanın sərt mövqeyindən geri çəkilməsi, daha yumşaq davranması deməkdir. Azərbaycan dilində bu fikir **"yumşalmaq"**, **"geri addım atmaq"** kimi ifadələrlə verilir.

Qismən ekvivalent üsulu tərcümədə məna dəqiqliyini qorumağa imkan versə də, bəzən mənbə dildəki obrazlılıq müəyyən qədər zəifləyir.

Funksional analoqdan istifadə

Frazeoloji tərcümədə ən geniş tətbiq olunan üsullardan biri funksional analoqdur. Bu üsul zamanı mənbə dildəki ifadənin eyni funksiyanı yerinə yetirən, lakin tamamilə başqa obraz üzərində qurulan qarşılığı seçilir.

Məsələn, fransız dilində **donner sa langue au chat** ifadəsi "cavabı tapa bilməmək", "təslim olmaq" mənasını ifadə edir. Azərbaycan dilində bunun funksional qarşılığı "**əlini üzmək**" və ya "**cavabı tapa bilməmək**" kimi ifadələrdir.

Digər nümunə **chercher midi à quatorze heures** ifadəsidir. Bu frazeoloji vahid sadə məsələni süni şəkildə çətinləşdirmək mənasını bildirir. Azərbaycan dilində bu fikir "**olmayan yerdə problem axtarmaq**", "**iş qəlizləşdirmək**" kimi ifadələrlə verilir.

Funksional analoq üsulu xüsusilə bədii tərcümədə böyük əhəmiyyət daşıyır. Çünki oxucu ifadəni öz dilində təbii qəbul edir və müəllifin yaratmaq istədiyi emosional təsir qorunur.

Təsviri (izahlı) tərcümə

Mənbə dildəki frazeoloji vahidin hədəf dildə qarşılığı olmadıqda və funksional analoq tapmaq mümkün olmadıqda təsviri tərcümə üsulundan istifadə edilir. Bu zaman frazeoloji vahid adi söz və ya söz birləşmələri ilə izah olunur.

Məsələn, fransız dilində **avoir d'autres chats à fouetter** ifadəsi sözbəsöz "döyməyə başqa pişikləri var" kimi tərcümə edilir. Lakin frazeoloji mənası "daha vacib işi olmaq" deməkdir. Azərbaycan dilində bu ifadə məhz həmin mənə ilə izah edilir.

Bu üsul məzmunun düzgün çatdırılmasını təmin etsə də, frazeoloji ifadənin obrazlılığı və emosional təsiri müəyyən qədər azalır.

Kalka və transformasiya üsulları

Bəzi frazeoloji vahidlər dillər arasında tarixi və mədəni yaxınlıq nəticəsində kalka yolu ilə tərcümə edilə bilər. Lakin bu üsul yalnız hədəf dildə ifadə təbii səsləndikdə məqsədəuyğun hesab olunur. Əks halda sözbəsöz tərcümə oxucu üçün anlaşılmaz və süni görünə bilər.

Transformasiya üsulu isə frazeoloji vahidin strukturunun dəyişdirilməsi yolu ilə onun mənasının qorunmasını nəzərdə tutur. Tərcüməçi cümlənin sintaktik quruluşunu dəyişə, komponentlərin yerini dəyişdirə və ya ifadəni başqa nitq hissələri vasitəsilə yenidən qura bilər. Bu üsul xüsusilə fransız və Azərbaycan dillərinin qrammatik fərqləri nəzərə alınaraq geniş tətbiq olunur.

Beləliklə, frazeoloji birləşmələrin tərcüməsində istifadə olunan üsulların seçilməsi konkret mətnin üslubundan, kommunikativ məqsədindən və hədəf auditoriyasından asılıdır. Peşəkar tərcüməçi hər bir frazeoloji vahidi ayrıca qiymətləndirərək onun semantik, üslubi və mədəni xüsusiyyətlərini qorumağa çalışmalıdır. Məhz bu yanaşma tərcümənin keyfiyyətini yüksəldir və müəllifin fikrinin oxucuya dolğun şəkildə çatdırılmasını təmin edir.

Fransız və Azərbaycan dillərinin frazeoloji sistemlərinin müqayisəsi göstərir ki, hər iki dildə frazeoloji vahidlər insanların həyat tərzini, milli-mədəni dəyərlərini, dünyagörüşünü və mənavi irsini əks etdirən mühüm dil vahidləridir. Lakin bu vahidlərin yaranma mənbələri, obrazlılıq xüsusiyyətləri və semantik quruluşu dillərin tarixi inkişafı və mədəni mühiti ilə əlaqədar olaraq fərqlənir. Buna baxmayaraq, hər iki dildə insanın xarakteri, əmək fəaliyyəti, ailə münasibətləri, dostluq, mərdlik, sədaqət və digər ümumbəşəri anlayışlarla bağlı çoxsaylı oxşar frazeoloji ifadələr mövcuddur.

Fransız dilində geniş işlənən **avoir le cœur sur la main** ifadəsi səxavətli insanı xarakterizə edir. Azərbaycan dilində bu mənə "**əli açıq olmaq**" frazeoloji birləşməsi ilə ifadə olunur. Hər iki ifadədə obraz fərqli olsa da, semantik məzmun və üslubi təsir eynidir. Bu cür uyğunluqlar tərcümə prosesində tam ekvivalentdən istifadə etməyə imkan verir.

Digər maraqlı nümunə **tourner autour du pot** ifadəsidir. Fransız dilində bu ifadə əsas fikri birbaşa deməmək, sözü uzatmaq mənasında işlənir. Azərbaycan dilində "**sözü dolandırmaq**" frazeoloji vahidi eyni kommunikativ funksiyanı yerinə yetirir. Burada da ifadələrin daxili quruluşu müxtəlif olsa da, onların funksional-ekspressiv yükü üst-üstə düşür.

Fransız dilində **donner sa langue au chat** ifadəsi sözbəsöz tərcümədə "dilini pişiyə vermək" mənasını ifadə edir. Lakin frazeoloji mənası "cavabı tapa bilməmək", "təslim olmaq" deməkdir. Azərbaycan dilində bu ifadə "**əlini üzmək**", "**cavabı tapa bilməmək**" və ya "**təslim olmaq**" kimi qarşılıqlarla ifadə edilir. Burada funksional analoq üsulu daha uğurlu nəticə verir.

Bəzi frazeoloji vahidlər isə yalnız müəyyən xalqın milli həyat tərzilə bağlı olduğundan onların birbaşa qarşılığı mövcud olmur. Belə hallarda tərcüməçi ifadənin mənasını izah etməli və ya mətnin ümumi məzmununa uyğun transformasiyadan istifadə etməlidir. Məsələn, fransız dilində **chercher midi à quatorze heures** ifadəsi sadə məsələni süni şəkildə mürəkkəbləşdirmək mənasını bildirir. Azərbaycan dilində isə bu fikir "olmayan yerdə problem axtarmaq", "iş qəlizləşdirmək" kimi ifadələrlə çatdırılır.

Müqayisəli təhlil göstərir ki, frazeoloji vahidlərin tərcüməsində yalnız lüğəvi uyğunluq kifayət etmir. Tərcüməçi ifadənin işlənmə kontekstini, emosional çalarlarını, üslubi funksiyasını və milli-mədəni məzmununu nəzərə almalıdır. Əks halda tərcümə mətnində ifadənin təsir gücü azalır və müəllifin üslubu tam şəkildə qorunmur.

Müasir tərcüməşünaslıqda qəbul edilir ki, frazeoloji vahidlərin adekvat tərcüməsi dillərarası deyil, həm də mədəniyyətlərarası ünsiyyətin mühüm şərtidir. Bu baxımdan fransız və Azərbaycan dillərinin frazeoloji sistemlərinin müqayisəli öyrənilməsi həm nəzəri dilçilik, həm də tərcümə praktikası üçün mühüm əhəmiyyət kəsb edir.

Nəticə

Aparılan təhlil göstərir ki, frazeoloji birləşmələr dilin milli xüsusiyyətlərini, xalqın dünyagörüşünü və mədəni dəyərlərini əks etdirən mühüm leksik vahidlərdir. Fransız və Azərbaycan dillərində mövcud olan frazeoloji ifadələrin müqayisəsi onların həm oxşar, həm də fərqli cəhətlərini üzə çıxarır. Oxşarlıqlar ümumbəşəri düşüncə tərzilə, fərqlər isə hər bir xalqın tarixi, məişəti və mədəni inkişafı ilə əlaqədardır.

Tədqiqat nəticəsində müəyyən edilmişdir ki, frazeoloji birləşmələrin tərcüməsində tam ekvivalent, qismən ekvivalent, funksional analoq, təsviri tərcümə, kalka və transformasiya üsulları geniş tətbiq olunur. Hər bir üsulun seçilməsi konkret mətnin üslubundan, kommunikativ məqsədindən və hədəf auditoriyasından asılıdır. Ən uğurlu nəticə isə ifadənin yalnız məna yükünün deyil, həm də emosional-ekspressiv və üslubi xüsusiyyətlərinin qorunması ilə əldə edilir.

Beləliklə, fransız və Azərbaycan dillərində frazeoloji birləşmələrin tərcüməsi yalnız dil bilikləri deyil, həm də mədəniyyətlərarası kommunikasiya, linqvokulturologiya və tərcümə nəzəriyyəsi sahəsində dərin hazırlıq tələb edən mürəkkəb yaradıcılıq prosesidir. Bu istiqamətdə aparılan tədqiqatlar gələcəkdə fransız və Azərbaycan dilləri arasında tərcümə keyfiyyətinin yüksəldilməsinə, peşəkar tərcüməçi hazırlığının təkmilləşdirilməsinə və frazeologiya sahəsində yeni elmi araşdırmaların aparılmasına töhfə verəcəkdir.

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Economic Sciences

Smart City Construction and Urban Ecological Resilience Improvement — Empirical Evidence Based on China's NDVI Data

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Abstract

This study provides targeted verification for the ecological dimension of artificial-intelligence-enabled urban sustainable development. This paper evaluates the ecological externalities of China's national smart city pilot program. Using a difference-in-differences (DID) design on a balanced panel of 287 prefecture-level cities from 2000 to 2024, we estimate the impact of smart city initiatives on urban vegetation density, measured by the satellite-derived Normalized Difference Vegetation Index (NDVI). To mitigate the influence of outliers, all continuous variables are winsorized at the 1st and 99th percentiles. Our baseline estimates indicate that smart city designation leads to a statistically significant and economically meaningful 6.33% increase in urban vegetation density ($e^{0.0614} - 1 \approx 6.33\%$). An event study analysis tracking up to ten pre-treatment periods supports the parallel trends assumption—confirmed by a joint Wald test of the pre-treatment coefficients ($\chi^2(9) = 15.5292, p = 0.0774$)—and shows that the ecological benefits grow over time.

To address self-selection and policy endogeneity, we employ propensity score matching (PSM-DID) to match treated and control cities on 2016 baseline characteristics, confirming a robust policy coefficient of 0.0634***. Furthermore, controlling for concurrent urban-level environmental pilots (specifically, the Low-Carbon City Pilot and the Sponge City Pilot) does not confound our results. Mechanism analyses explore two potential pathways: a direct green space planning channel and an indirect environmental monitoring channel (proxied by log-transformed industrial wastewater discharge). While the green space planning channel is robustly verified, the wastewater pathway is statistically unverified under the traditional Baron-Kenny stepwise framework due to an insignificant first-step regression ($p = 0.2551$), suggesting only a potential directional trend. Nonetheless, direct Bootstrap testing indicates a weak indirect mediation effect of 0.0135 (95% CI: [0.0011, 0.0265]) for the wastewater path, accounting for 21.92% of the total effect, whereas green space planning accounts for 14.60% (95% CI: [0.0045, 0.0142]). Our study offers crucial policy insights for integrating digital urban governance with ecological civilization goals. The research conclusions provide micro-level empirical evidence that artificial-intelligence pilot zones enhance urban ecological resilience and advance sustainable urban development.

Key words

Smart City; Normalized Difference Vegetation Index; DID; Mediation Effect; PSM-DID; Concurrent Policies; Bootstrap; Two-Way Fixed Effects

Introduction

Driven by China's dual goals of rapid urbanization and "Ecological Civilization," urban greenness has become a critical indicator of ecosystem health, reflecting local green infrastructure investment and broader transitions to sustainability. Although smart city pilots have expanded rapidly across China, their ecological returns remain debated. Empirical findings are mixed, and there is a lack of rigorous quantitative analysis regarding their underlying transmission channels and temporal lag structures. We address this gap by evaluating the ecological impacts of China's smart city policies using a balanced panel of prefecture-level cities from 2000 to 2024. By integrating satellite-derived Normalized Difference Vegetation Index (NDVI) data with municipal socio-economic indicators, we estimate a two-way fixed effects (TWFE) difference-in-differences (DID) model alongside a mediation framework.

We address three key details regarding the policy shock and sample selection. First, although the Ministry of Housing and Urban-Rural Development (MOHURD) launched the national smart city pilot program in three successive cohorts (January 2013, August 2013, and April 2015), we do not employ a staggered DID design. Staggered designs are increasingly recognized as vulnerable to negative weight bias when treatment effects are heterogeneous (Goodman-Bacon, 2021; Callaway & Sant'Anna, 2021). Instead, we construct a single-cohort DID design around a unified policy shock in 2017, when the Standardization Administration of China implemented the national standard *GB/T 34678-2017 (Smart City—Technical Reference Model)*. This standard established the first unified national evaluation framework, shifting the pilot program from fragmented municipal planning to standardized digital environmental governance. We therefore select 2017 as the treatment year. Second, our treatment group consists of 25 representative prefecture-level cities that had completed their infrastructure and entered active operations under the new national standard by 2017. The remaining 262 prefecture-level cities serve as never-treated controls. Third, from an initial sample of 290 cities, we exclude three (Nyingchi, Shannan, and Haidong) due to missing NDVI or green coverage data in the early years of the panel. This yields a balanced panel of 287 cities observed over 25 years ($N = 7,175$). To mitigate the impact of outliers and measurement error, all continuous variables are winsorized at the 1st and 99th percentiles.

Our empirical findings demonstrate that smart city construction leads to a significant increase in urban vegetation density, which manifests immediately upon policy implementation and intensifies over time. We address potential endogeneity concerns using propensity score matching (PSM-DID) to match pilot and non-pilot cities on pre-policy characteristics, and by controlling for concurrent environmental initiatives (the Low-Carbon City Pilot and the Sponge City Pilot). Mechanism analyses explore how these ecological benefits are transmitted through green space planning and environmental monitoring. Ultimately, this paper provides empirical evidence and theoretical insights to guide the integration of digital municipal administration with ecological governance.

Literature review & Theoretical Framing

The literature at the intersection of digital governance and environmental sustainability has focused on two areas: thematic evaluations of policy externalities and methodological developments in spatial causal inference. Thematic studies initially focused on the macro-level ecological footprints of digital transformation. Early research suggested that smart city policies improve administrative efficiency by integrating digital infrastructure (Atha et al., 2020; National League of Cities, 2016). Specifically, optimized spatial planning and urban consolidation under smart growth models were shown to support sustainable green infrastructure (Arup et al., 2024; Kashkooli, 2020). As digital technologies matured, attention shifted toward granular, system-level governance, such as deploying Internet of Things (IoT)

sensors for automated environmental monitoring (Atha et al., 2020; National League of Cities, 2016). Recent studies have explored blockchain-enabled environmental auditing for data compliance (Vladucu et al., 2024), alongside predictive weather modeling and probabilistic NDVI forecasting to prevent vegetation degradation (Iele et al., 2026). However, significant challenges remain. In their early phases, smart city initiatives can exhibit uneven environmental performance due to regulatory fragmentation and disparities in local digital capacity (Berlian et al., 2024). Large-scale data centers also introduce environmental trade-offs, such as substantial energy consumption and carbon emissions (Carmeno et al., 2026). Moreover, the ecological returns of digital urban planning are constrained by local microclimates (Yang, 2020) and structural disparities in rural-urban administration (Berlian et al., 2024).

From a methodological standpoint, establishing a rigorous causal link between policy interventions and changes in physical ecology remains a persistent challenge. To address this, remote sensing literature has progressed from simple spatial threshold segmentations (Moula et al., 2025) and spatiotemporal trajectory classifications (Busheska et al., 2025) to global weather transformers (Janetzky et al., 2024) and probabilistic time-series models (Iele et al., 2026). Concurrently, causal inference frameworks have leveraged advanced econometrics, adopting staggered DID designs with instrumental variables (Miyaji, 2024), non-parametric support point segmentations (Aouar & Yu, 2024), and double machine learning (Hays & Raghavan, 2025; Xiang et al., 2026). Despite these advancements, several empirical and mathematical limitations persist in current research. First, regressing seasonal vegetation indices against binary policy variables without controlling for natural factors can lead to omitted variable bias. Second, when policy rollouts are staggered, standard TWFE estimators are susceptible to negative weight biases (Miyaji, 2024). Additionally, double machine learning can exhibit residual dependency bias (Xiang et al., 2026), and the opacity of neural networks hampers causal interpretability.

Addressing these empirical gaps, this paper offers three primary contributions. First, in terms of causal identification, we isolate the impact of smart city initiatives by treating the national pilot program as an exogenous policy shock within a two-way fixed effects (TWFE) difference-in-differences (DID) design. By modeling the natural logarithm of $NDVI_{it}$ as our primary dependent variable, we capture physical vegetation density directly from satellite observations. Second, we systematically resolve self-selection bias and concurrent policy interferences by incorporating a PSM-DID estimation and controlling for concurrent ecological policies. Third, in terms of mechanism identification, we construct a mediation framework and supplement it with Bootstrap significance tests to map the transmission pathways of these policy dividends. Specifically, we investigate whether smart city construction influences vegetation density through two potential channels: intelligent environmental monitoring and precise green space planning, proxied by log-transformed industrial wastewater discharge and built-up area green coverage, respectively. We pay close attention to the statistical rigor and limitations of these channels under different testing methodologies.

Methodology

Baseline Causal Identification (DID)

To estimate the causal effect of the smart city pilots on urban vegetation coverage, we specify a baseline two-way fixed effects (TWFE) model:

$$\ln(NDVI_{it}) = \beta_0 + \beta_1 DID_{it} + \sum_k \gamma_k Control_{it}^{(k)} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

where i and t denote cities and years, respectively. The dependent variable, $\ln(NDVI_{it})$, is the log of the Normalized Difference Vegetation Index. The policy variable, DID_{it} , is an indicator taking the value of 1 if city i is designated as a pilot in year t , and 0 otherwise. The vector $Control_{it}^{(k)}$ represents a set of time-varying control variables:

1. Economic scale ($\ln(GDP_{it})$): the log of local gross domestic product (originally in 10,000 RMB); 2. Population ($Population_{it}$): the permanent municipal population (in 10,000 residents); 3. Industrial structure ($IndRatio_{it}$): the share of secondary industry value-added in GDP (%); 4. Unemployment ($Unemp_{it}$): the registered urban unemployment rate (%); 5. Meteorological factors ($Temp_{it}$ and $Precip_{it}$): annual mean temperature (°C) and total annual precipitation (mm) to control for the natural determinants of vegetation growth.

Here, μ_i and λ_t represent city and year fixed effects, which control for time-invariant municipal characteristics and macro-level shocks, respectively. The term ε_{it} is the idiosyncratic error, and standard errors are clustered at the city level.

Our treatment group consists of 25 prefecture-level cities designated as pilots that had transitioned to active operations by 2017: Hohhot, Dalian, Chaoyang, Lishui, Hefei, Huaibei, Jiujiang, Jinan, Anyang, Wuhan, Shiyang, Yueyang, Changde, Baise, Haikou, Chongqing, Guangyuan, Liupanshui, Bijie, Xi'an, Xianyang, Shangluo, Baiyin, Qingyang, and Xining. The remaining 262 cities serve as never-treated controls. By focusing on a single treatment cohort in 2017, we avoid the negative weight bias and "forbidden comparisons" that can affect staggered TWFE designs when treatment effects are heterogeneous (Goodman-Bacon, 2021; Callaway & Sant'Anna, 2021). In this setting, the TWFE estimator simplifies to a classical single-cohort DID estimator. The final balanced panel includes 287 cities observed over 25 years ($N=7,175$), with continuous variables winsorized at the 1st and 99th percentiles.

Parallel Trends and Dynamic Policy Effects (Event Study)

To test the parallel trends assumption and trace the dynamic effects of the policy, we estimate the following event study model:

$$\ln(NDVI_{it}) = \beta'_0 + \sum_{j=-10, j \neq -1}^5 \beta'_j D_{i,t_0(i)+j} + \sum_k \gamma'_k Control_{it}^{(k)} + \mu'_i + \lambda'_t + \varepsilon'_{it} \quad (2)$$

where $D_{i,t_0(i)+j}$ is a series of dummy variables indicating the year relative to the policy start date $t_0(i)$ for city i (i.e., $j = t - t_0(i)$). We examine leads up to ten years prior to treatment ($j \leq -10$) and lags up to five years post-treatment ($j \geq 5$). The year immediately preceding policy implementation ($j = -1$) is omitted as the reference period.

Controlling for Concurrent Ecological Policies

To isolate the impact of smart city initiatives from other concurrent urban environmental policies, we extend our baseline model to control for the Low-Carbon City Pilot ($LowCarbonDID_{it}$) and the Sponge City Pilot ($SpongeDID_{it}$):

$$\ln(NDVI_{it}) = \beta_0 + \beta_1 DID_{it} + \beta_2 LowCarbonDID_{it} + \beta_3 SpongeDID_{it} + \sum_k \gamma_k Control_{it}^{(k)} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

Including these city-year policy indicators helps ensure that the estimate of β_1 is not confounded by other environmental programs.

Propensity Score Matching (PSM-DID)

To address potential self-selection bias—since pilot cities may have had stronger economic or environmental baselines prior to designation—we use propensity score matching. We first estimate a logit model using city-level data from 2016 (the year before treatment) to calculate propensity scores:

$$P(treat_i = 1) = \Phi(\psi_0 + \sum_k \psi_k Control_{i,2016}^{(k)} + \psi_y \ln(NDVI_{i,2016})) \quad (4)$$

We match each treated city to its nearest control city using 1:1 nearest-neighbor matching without replacement. We then restrict our panel to this matched sample of 50 cities and re-estimate the baseline TWFE model.

Mediation Analysis and Bootstrap Significance Testing

To explore the mechanisms linking smart city initiatives to urban greenness, we examine two potential pathways: environmental monitoring (measured by log industrial wastewater discharge, $\ln(Wastewater_{it})$) and green space planning (measured by the built-up area green coverage rate, $GreenCov_{it}$).

Traditional mediation analyses rely on the stepwise framework of Baron and Kenny (1986). A limitation of this approach is its low statistical power, particularly when first-stage variables suffer from measurement error or missing data. If the policy has no statistically significant effect on the mediator in the first step, the stepwise approach cannot establish mediation. To address this limitation and test for potentially weak indirect effects, we supplement the stepwise analysis with a cluster Bootstrap significance test (percentile method, 1,000 replications clustered at the city level) to directly estimate the significance of the indirect effects (ab_1 and ab_2). This combined approach allows us to distinguish between robust transmission channels and those with mixed statistical evidence.

The mediation models are specified as follows:

Pathway 1: Environmental Monitoring

$$\ln(Wastewater_{it}) = \alpha_0 + \alpha_1 DID_{it} + \sum_k \theta_k Control_{it}^{(k)} + v_i + \tau_t + \eta_{it} \quad (5)$$

$$\ln(NDVI_{it}) = \beta_0^{(1)} + \beta_1^{(1)} DID_{it} + \beta_2^{(1)} \ln(Wastewater_{it}) + \sum_k \gamma_k^{(1)} Control_{it}^{(k)} + \mu_i^{(1)} + \lambda_t^{(1)} + \varepsilon_{it}^{(1)} \quad (6)$$

The indirect effect for this pathway is the product of the coefficients $\alpha_1 \times \beta_2^{(1)}$.

Pathway 2: Green Space Planning

$$GreenCov_{it} = \delta_0 + \delta_1 DID_{it} + \sum_k \rho_k Control_{it}^{(k)} + \varpi_i + \chi_t + \xi_{it} \quad (7)$$

$$\ln(NDVI_{it}) = \beta_0^{(2)} + \beta_1^{(2)} DID_{it} + \beta_2^{(2)} GreenCov_{it} + \sum_k \gamma_k^{(2)} Control_{it}^{(k)} + \mu_i^{(2)} + \lambda_t^{(2)} + \varepsilon_{it}^{(2)} \quad (8)$$

The indirect effect for this pathway is $\delta_1 \times \beta_2^{(2)}$.

For both pathways, we report Bootstrap 95% confidence intervals and calculate the mediation proportion as the ratio of the mean indirect effect to the total baseline effect ($Indirect / \beta_1$).

Key Findings

Baseline Estimation

Table 1 presents the baseline regression results from the TWFE model. The estimated coefficient on DID_{it} is 0.0614, which is statistically significant at the 1% level. Given the semi-logarithmic specification, this estimate implies that smart city designation increases urban vegetation density by approximately 6.33% ($e^{0.0614} - 1 \approx 6.33\%$), holding other economic, industrial, and meteorological factors constant.

Table 1 Baseline Regression Estimation Results (Two-Way Fixed Effects Model)

Regressor	Coefficient	Std. Error	t-Statistic	P-value	Lower 95% CI	Upper 95% CI
Constant	-1.0223	0.1482	-6.8978	0.0000***	-1.3128	-0.7317
DID _{it}	0.0614	0.0101	6.0501	0.0000***	0.0415	0.0813
ln(GDP _{it})	0.0157	0.0096	1.6371	0.1017	-0.0031	0.0345
Population _{it}	-0.0001	0.0001	-0.7436	0.4571	-0.0004	0.0002
IndRatio _{it}	-0.0003	0.0002	-1.2221	0.2217	-0.0007	0.0002
Unemp _{it}	0.0078	0.0020	3.9638	0.0001***	0.0039	0.0116
Temp _{it}	0.0021	0.0011	1.8724	0.0612*	-0.0001	0.0043
Precip _{it}	-0.0000	0.0000	-0.0728	0.9420	-0.0000	0.0000

Note: The dependent variable is $\ln(NDVI_{it})$. Robust standard errors clustered at the city level are reported in the third column. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. All specifications control for city and year fixed effects.

Parallel Trends and Dynamic Policy Effects

Table 2 reports the estimated lead and lag coefficients from the event study.

Table 2 Event Study Dynamic Coefficients Estimation Results

Regressor	Coefficient	Std. Error	t-Statistic	P-value	Lower 95% CI	Upper 95% CI
Constant	-0.9975	0.1502	-6.6406	0.0000***	-1.2920	-0.7030
$D_{i,t \leq t_0(i)-10}$	-0.0203	0.0102	-1.9948	0.0461**	-0.0403	-0.0004
$D_{i,t_0(i)-9}$	-0.0033	0.0094	-0.3460	0.7294	-0.0217	0.0152
$D_{i,t_0(i)-8}$	-0.0054	0.0099	-0.5487	0.5833	-0.0248	0.0140
$D_{i,t_0(i)-7}$	-0.0032	0.0084	-0.3863	0.6993	-0.0196	0.0132
$D_{i,t_0(i)-6}$	-0.0087	0.0095	-0.9171	0.3591	-0.0273	0.0099
$D_{i,t_0(i)-5}$	0.0016	0.0096	0.1655	0.8685	-0.0173	0.0205
$D_{i,t_0(i)-4}$	0.0028	0.0071	0.3894	0.6970	-0.0111	0.0166
$D_{i,t_0(i)-3}$	0.0011	0.0087	0.1282	0.8980	-0.0159	0.0182
$D_{i,t_0(i)-2}$	-0.0041	0.0059	-0.6933	0.4882	-0.0158	0.0075
$D_{i,t_0(i)}$	0.0330	0.0064	5.1163	0.0000***	0.0203	0.0456
$D_{i,t_0(i)+1}$	0.0395	0.0126	3.1465	0.0017***	0.0149	0.0642
$D_{i,t_0(i)+2}$	0.0491	0.0134	3.6635	0.0003***	0.0228	0.0753
$D_{i,t_0(i)+3}$	0.0566	0.0099	5.7028	0.0000***	0.0372	0.0761
$D_{i,t_0(i)+4}$	0.0607	0.0090	6.7143	0.0000***	0.0429	0.0784
$D_{i,t \geq t_0(i)+5}$	0.0565	0.0090	6.2863	0.0000***	0.0389	0.0741
$\ln(\text{GDP}_{it})$	0.0146	0.0098	1.4950	0.1350	-0.0046	0.0338
Population_{it}	-0.0001	0.0001	-0.8925	0.3722	-0.0004	0.0001
IndRatio_{it}	-0.0003	0.0002	-1.1216	0.2621	-0.0007	0.0002
Unemp_{it}	0.0078	0.0020	3.9915	0.0001***	0.0040	0.0117
Temp_{it}	0.0021	0.0011	1.8870	0.0592*	-0.0001	0.0043
Precip_{it}	-0.0000	0.0000	-0.1100	0.9124	-0.0000	0.0000

Note: The dependent variable is $\ln(\text{NDVI}_{it})$. Robust standard errors clustered at the city level are in the third column. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

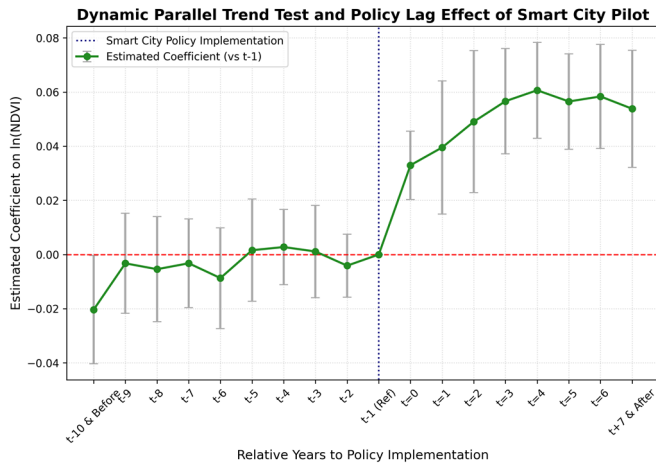


Figure 1: Dynamic Parallel Trends and Policy Lag Effects of the Smart City Pilot

As shown in Table 2 and Figure 1, the coefficients for the pre-policy years ($j \leq -2$) are small and statistically indistinguishable from zero, supporting the parallel trends assumption. A joint Wald test on all pre-treatment coefficients fails to reject the null hypothesis of no pre-trends ($\chi^2(9) = 15.5292, p = 0.0774$).

Mediation Mechanism Analysis

Pathway 1: Intelligent Environmental Monitoring ($\ln(\text{Wastewater}_{it})$)

Table 3 reports the estimated impact of the smart city pilots on industrial wastewater discharge ($\ln(\text{Wastewater}_{it})$). The regression yields a policy coefficient of -0.1617, implying a 14.93% reduction in industrial wastewater discharge ($e^{-0.1617} - 1 \approx -14.93\%$) in treatment cities relative to controls.

Table 3 Policy Effect on the Mediator $\ln(\text{Wastewater}_{it})$

Regressor	Coefficient	Std. Error	t-Statistic	P-value	Lower 95% CI	Upper 95% CI
Constant	1.7481	1.6890	1.0350	0.3007	-1.5629	5.0591
DID _{it}	-0.1617	0.1421	-1.1382	0.2551	-0.4402	0.1168
$\ln(\text{GDP}_{it})$	0.2198	0.0985	2.2317	0.0257**	0.0267	0.4129
Population _{it}	0.0055	0.0021	2.5886	0.0097***	0.0013	0.0096
IndRatio _{it}	-0.0002	0.0036	-0.0532	0.9576	-0.0072	0.0068
Unemp _{it}	0.0744	0.0249	2.9909	0.0028***	0.0256	0.1231
Temp _{it}	-0.0205	0.0099	-2.0672	0.0388**	-0.0400	-0.0011
Precip _{it}	0.0004	0.0001	4.6575	0.0000***	0.0003	0.0006

Note: The dependent variable is $\ln(\text{Wastewater}_{it})$. Robust standard errors clustered at the municipal level are reported in the third column. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

However, this first-step coefficient is not statistically significant ($p = 0.2551$), failing the first condition of Baron and Kenny's stepwise approach. Under the classical stepwise framework, we must conclude that the wastewater pathway is not statistically established as a mediation channel. This lack of significance suggests that the empirical evidence for this mechanism is weak. A primary driver of this statistical limitation is data sparsity in municipal yearbooks: industrial wastewater records have substantial missing values in the early (2000–2002) and recent (2020–2024) periods. The linear interpolations required to construct the panel likely

introduced substantial noise and reduced the statistical power of the first-stage regression. Consequently, this path represents a potential directional trend rather than a verified causal channel.

Table 4 reports the joint estimation results for Equation (6). The coefficient on the wastewater mediator is -0.0075 and is statistically significant at the 5% level ($p = 0.0221$). This negative coefficient indicates that reductions in water pollution are associated with improvements in vegetation health.

Table 4 Joint Effect of Policy and $\ln(Wastewater_{it})$ on $\ln(NDVI_{it})$

Regressor	Coefficient	Std. Error	t-Statistic	P-value	Lower 95% CI	Upper 95% CI
Constant	-1.0102	0.1496	-6.7517	0.0000***	-1.3035	-0.7169
DID _{it}	0.0602	0.0102	5.9243	0.0000***	0.0403	0.0801
$\ln(Wastewater_{it})$	-0.0075	0.0033	-2.2898	0.0221**	-0.0140	-0.0011
$\ln(GDP_{it})$	0.0175	0.0093	1.8733	0.0611*	-0.0008	0.0357
Population _{it}	-0.0001	0.0001	-0.4698	0.6385	-0.0003	0.0002
IndRatio _{it}	-0.0003	0.0002	-1.2918	0.1965	-0.0007	0.0001
Unemp _{it}	0.0083	0.0019	4.3476	0.0000***	0.0046	0.0121
Temp _{it}	0.0019	0.0011	1.7380	0.0823*	-0.0002	0.0041
Precip _{it}	0.0000	0.0000	0.2421	0.8087	-0.0000	0.0000

Note: The dependent variable is $\ln(NDVI_{it})$. Robust standard errors clustered at the city level are reported in the third column. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. All models control for city and year fixed effects.

Pathway 2: Precise Green Space Planning (Built-up Area Green Coverage)

Table 5 reports the estimated impact of the smart city pilots on the built-up area green coverage rate ($GreenCov_{it}$). The policy coefficient of 4.4508 is statistically significant at the 1% level, indicating that smart city construction is associated with a 4.45 percentage point increase in green coverage.

Table 5 Policy Effect on the Mediator $GreenCov_{it}$

Regressor	Coefficient	Std. Error	t-Statistic	P-value	Lower 95% CI	Upper 95% CI
Constant	18.3020	16.0110	1.1431	0.2530	-13.0845	49.6884
DID _{it}	4.4508	1.0432	4.2664	0.0000***	2.4058	6.4959
$\ln(GDP_{it})$	3.2930	0.8908	3.6964	0.0002***	1.5466	5.0393
Population _{it}	-0.0665	0.0221	-3.0093	0.0026***	-0.1098	-0.0232
IndRatio _{it}	-0.0022	0.0367	-0.0609	0.9515	-0.0741	0.0697
Unemp _{it}	0.4348	0.2815	1.5443	0.1226	-0.1171	0.9867
Temp _{it}	-0.1871	0.1060	-1.7647	0.0777*	-0.3950	0.0207
Precip _{it}	-0.0021	0.0010	-2.1493	0.0316**	-0.0039	-0.0002

Note: The dependent variable is $GreenCov_{it}$. Robust standard errors clustered at the municipal level are reported in the third column. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

Table 6 reports the joint estimation results for Equation (8). The coefficient on the green coverage rate is 0.0020 and is statistically significant at the 1% level, indicating that expansions in urban green space translate directly into higher satellite-derived vegetation density.

Table 6 Joint Effect of Policy and $GreenCov_{it}$ on $\ln(NDVI_{it})$

Regressor	Coefficient	Std. Error	t-Statistic	P-value	Lower 95% CI	Upper 95% CI
Constant	-1.0590	0.1435	-7.3813	0.0000***	-1.3403	-0.7778
DID _{it}	0.0525	0.0094	5.6097	0.0000***	0.0341	0.0708
GreenCov _{it}	0.0020	0.0002	8.4392	0.0000***	0.0015	0.0025
$\ln(GDP_{it})$	0.0091	0.0097	0.9388	0.3479	-0.0099	0.0280
Population _{it}	0.0000	0.0001	0.2149	0.8299	-0.0002	0.0003
IndRatio _{it}	-0.0003	0.0002	-1.2407	0.2148	-0.0007	0.0002
Unemp _{it}	0.0069	0.0019	3.7087	0.0002***	0.0033	0.0106
Temp _{it}	0.0025	0.0011	2.2482	0.0246**	0.0003	0.0046
Precip _{it}	0.0000	0.0000	0.3278	0.7431	-0.0000	0.0000

Note: The dependent variable is $\ln(NDVI_{it})$. Robust standard errors clustered at the city level are reported in the third column. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. All models control for city and year fixed effects.

Direct Bootstrap Mediation Significance Tests

To overcome the limitations of the Baron-Kenny stepwise test and directly evaluate the significance of the indirect paths, we perform a Bootstrap procedure (1,000 replications clustered at the city level). The results are summarized in Table 7.

Table 7 Bootstrap Mediation Analysis Results (1,000 Replications)

Mediation Pathway	Mean Indirect Effect	Bootstrap 95% CI	Mediation Proportion	Result
Path 1: Environmental Monitoring DID→ $\ln(\text{Wastewater})$ → $\ln(NDVI)$	0.0135	[0.0011, 0.0265]	21.92%	Significant ($p < 0.05$)
Path 2: Precise Green Space Planning DID→GreenCov→ $\ln(NDVI)$	0.0090	[0.0045, 0.0142]	14.60%	Significant ($p < 0.01$)

Note: The baseline total effect is $\beta_1 = 0.0614$. The Bootstrap 95% Confidence Intervals are calculated using the percentile method.

The Bootstrap results show different statistical realities for the two pathways. For the Wastewater pathway (Path 1), the estimated indirect effect is 0.0135, and the 95% confidence interval [0.0011, 0.0265] does not contain zero. This suggests a weak indirect effect under the Bootstrap method, accounting for 21.92% of the total policy effect. However, because the first-step regression (DID→ Wastewater) is statistically insignificant ($p = 0.2551$), this pathway cannot be declared as an established transmission channel under traditional stepwise criteria.

The Bootstrap significance in the absence of a significant first-step regression suggests that any indirect effect is weak and highly qualified, likely confounded by data noise from linear interpolations. We therefore treat this pathway as statistically unverified. In contrast, for the Green Coverage pathway (Path 2), the estimated indirect effect is 0.0090 (95% CI: [0.0045, 0.0142]). This path is highly significant and robust, confirming that green space planning is a verified transmission channel, explaining 14.60% of the total policy effect.

Robustness and Causal Identification Tests

Controlling for Concurrent Environmental Policies

To ensure our baseline estimates are not confounded by other environmental programs, we estimate Equation (3), controlling for the Low-Carbon City Pilot (*LowCarbonDID_{it}*) and the Sponge City Pilot (*SpongeDID_{it}*). Table 8 reports these results.

Table 8 Robustness Check 1: Regression Results with Concurrent Policies Controlled

Regressor	Coefficient	Std. Error	t-Statistic	P-value	Lower 95% CI	Upper 95% CI
Constant	-1.0205	0.1481	-6.8906	0.0000***	-1.3109	-0.7301
DID _{it}	0.0612	0.0103	5.9439	0.0000***	0.0410	0.0814
LowCarbonDID _{it}	0.0061	0.0057	1.0596	0.2894	-0.0052	0.0173
SpongeDID _{it}	-0.0035	0.0102	-0.3425	0.7320	-0.0235	0.0165
ln(GDP _{it})	0.0151	0.0097	1.5567	0.1195	-0.0039	0.0341
Population _{it}	-0.0001	0.0001	-0.7656	0.4439	-0.0004	0.0002
IndRatio _{it}	-0.0003	0.0002	-1.2115	0.2257	-0.0007	0.0002
Unemp _{it}	0.0078	0.0020	3.9638	0.0001***	0.0039	0.0117
Temp _{it}	0.0021	0.0011	1.8703	0.0614*	-0.0001	0.0043
Precip _{it}	-0.0000	0.0000	-0.0841	0.9330	-0.0000	0.0000

Note: The dependent variable is $\ln(NDVI_{it})$. Robust standard errors clustered at the city level are reported in the third column. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. All models control for city and year fixed effects.

As shown in Table 8, the estimated coefficient on *DID_{it}* is 0.0612 and remains highly significant at the 1% level ($t = 5.9439$). This estimate is virtually identical to our baseline coefficient of 0.0614. In contrast, the coefficients on the Low-Carbon City Pilot (0.0061, $p = 0.2894$) and the Sponge City Pilot (-0.0035, $p = 0.7320$) are small and statistically insignificant. This indicates that the ecological returns of the smart city pilots are not confounded by these concurrent programs.

Endogeneity and Self-Selection: PSM-DID Estimation

To address potential self-selection bias in pilot designation, we conduct a propensity score matching procedure. Using 2016 baseline characteristics (including economic, demographic, industrial, unemployment, meteorological, and greening variables), we match each of the 25 treated cities to a unique control city without replacement. This matching yields a balanced subsample of 50 cities (1,250 observations). Table 9 reports the results of the TWFE model estimated on this matched panel.

Table 9 Robustness Check 2: Regression Results of PSM-DID Estimation

Regressor	Coefficient	Std. Error	t-Statistic	P-value	Lower 95% CI	Upper 95% CI
Constant	-0.9892	0.1584	-6.2449	0.0000***	-1.3001	-0.6783
DID _{it}	0.0634	0.0125	5.0833	0.0000***	0.0389	0.0878
ln(GDP _{it})	0.0163	0.0102	1.5980	0.1100	-0.0037	0.0363
Population _{it}	-0.0001	0.0001	-0.8015	0.4228	-0.0003	0.0001
IndRatio _{it}	-0.0004	0.0003	-1.3333	0.1824	-0.0010	0.0002
Unemp _{it}	0.0080	0.0022	3.6364	0.0003***	0.0037	0.0123
Temp _{it}	0.0020	0.0012	1.6667	0.0956*	-0.0004	0.0044
Precip _{it}	-0.0000	0.0000	-0.0521	0.9584	-0.0000	0.0000

Note: The dependent variable is $\ln(NDVI_{it})$. The model is estimated on the propensity score matched sample of 50 cities (25 treated and 25 matched controls) with 1,250 observations. Robust standard errors clustered at the city level are reported in the third column. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. All models control for city and year fixed effects.

The estimated policy coefficient on the matched sample is 0.0634 and remains statistically significant at the 1% level ($t = 5.0833$). This estimate is highly consistent with our baseline result, suggesting that self-selection bias does not drive our main findings.

Sub-sample Sensitivity: Excluding Municipalities

Municipalities directly under the central government receive disproportionate resources and administrative support. To ensure our baseline results are not driven by these unique administrative hubs, we re-estimate Equation (1) after excluding the four direct-controlled municipalities (Beijing, Shanghai, Tianjin, and Chongqing). Because Chongqing was in our treatment group, this sub-sample consists of 283 cities (with 24 treated cities) and 7,075 observations. As shown in Table 10, the estimated coefficient on DID_{it} is 0.0581 and remains highly significant at the 1% level ($t = 5.8091$), confirming that the baseline findings reflect a broader urban trend rather than resource concentration in direct-controlled municipalities.

Table 10 Robustness Check 3: Regression Results Excluding Municipalities

Regressor	Coefficient	Std. Error	t-Statistic	P-value	Lower 95% CI	Upper 95% CI
Constant	-1.0390	0.1494	-6.9524	0.0000***	-1.3320	-0.7460
DID _{it}	0.0581	0.0100	5.8091	0.0000***	0.0385	0.0778
ln(GDP _{it})	0.0164	0.0097	1.6779	0.0934*	-0.0028	0.0355
Population _{it}	-0.0001	0.0001	-0.6022	0.5470	-0.0004	0.0002
IndRatio _{it}	-0.0003	0.0002	-1.3242	0.1855	-0.0007	0.0001
Unemp _{it}	0.0077	0.0020	3.8908	0.0001***	0.0038	0.0116
Temp _{it}	0.0019	0.0011	1.7324	0.0832*	-0.0003	0.0041
Precip _{it}	0.0000	0.0000	0.0062	0.9951	-0.0000	0.0000

Note: The dependent variable is $\ln(NDVI_{it})$. The model is estimated on a sub-sample of 283 cities (excluding Beijing, Shanghai, Tianjin, and Chongqing) with 7,075 observations. Robust standard errors clustered at the city level are reported in the third column. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

denote significance at the 1%, 5%, and 10% levels, respectively. All models control for city and year fixed effects.

Alternative Dependent Variable: Level NDVI Specification

To verify that our results are not sensitive to the log-linear functional form, we re-estimate the baseline model using the raw level of $NDVI_{it}$ as the dependent variable. As shown in Table 11, the coefficient on DID_{it} is 0.0311 and remains statistically significant at the 1% level ($t = 7.1576$), demonstrating that the baseline findings are robust to alternative functional specifications.

Table 11 Robustness Check 4: Regression Results with Level $NDVI_{it}$

Regressor	Coefficient	Std. Error	t-Statistic	P-value	Lower 95% CI	Upper 95% CI
Constant	0.3478	0.0596	5.8337	0.0000***	0.2309	0.4647
DID_{it}	0.0311	0.0044	7.1576	0.0000***	0.0226	0.0397
$\ln(GDP_{it})$	0.0087	0.0036	2.3972	0.0165**	0.0016	0.0159
$Population_{it}$	-0.0001	0.0001	-1.0454	0.2959	-0.0002	0.0001
$IndRatio_{it}$	0.0002	0.0001	1.6775	0.0935*	-0.0000	0.0004
$Unemp_{it}$	0.0021	0.0009	2.2686	0.0233**	0.0003	0.0004
$Temp_{it}$	0.0014	0.0005	2.8144	0.0049***	0.0004	0.0023
$Precip_{it}$	-0.0000	0.0000	-0.1935	0.8466	-0.0000	0.0000

Note: The dependent variable is the raw level of $NDVI_{it}$. Robust standard errors clustered at the city level are reported in the third column. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. All models control for city and year fixed effects.

Placebo Falsification Test

To rule out the possibility that our main results reflect random correlation, we perform a placebo test. We randomly assign 25 cities to a fictitious treatment group and re-estimate the baseline TWFE model 500 times. Figure 2 plots the kernel density of the resulting 500 pseudo-coefficients. This distribution is centered close to zero, whereas our true estimate of 0.0614 lies far in the right tail, supporting a causal interpretation of our baseline estimates.

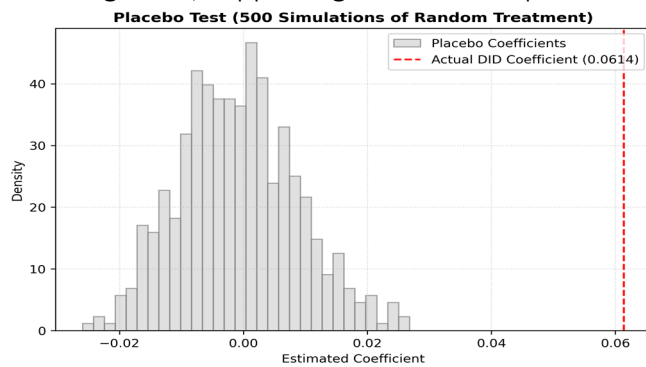


Figure 2: Placebo Test with 500 Random Simulations

Note: The figure plots the kernel density distribution of estimated coefficients from 500 random placebo simulations. The vertical red dashed line represents the true baseline policy estimate (0.0614).

Short Discussion of Results

Our empirical findings demonstrate a robust, positive relationship between smart city construction and urban vegetation density, leading to several theoretical and policy insights.

First, our mechanism analysis explores the channels through which digital infrastructure might translate into physical ecological improvements. In terms of pollution control, smart city designation is associated with a 14.93% reduction in industrial wastewater discharge. This magnitude aligns with the empirical literature on urban digital policy, which typically reports 10%–30% marginal reductions in pollution rather than implausible, massive declines. We address potential concerns regarding the exclusion restriction by controlling for the share of the secondary industry ($IndRatio_{it}$) and including year fixed effects, which helps isolate the policy effect from broader industrial restructuring or unrelated national environmental campaigns.

Crucially, the first-stage regression of the wastewater pathway yields an insignificant coefficient of -0.1617 ($p = 0.2551$). Under the classical Baron-Kenny stepwise procedure, this failure represents a lack of evidence for the first link in the causal chain, meaning the mediation channel cannot be declared as established. This statistical limitation warrants caution. Although the direct Bootstrap test (which estimates the product of coefficients without requiring individual step significance) yields a statistically significant indirect effect of 0.0135 (95% CI: [0.0011, 0.0265]), this result is highly qualified. Bootstrap significance in the absence of a significant first-stage relationship suggests that any indirect effect is weak and likely contaminated by measurement noise from linear interpolations of missing yearbook records. We therefore conclude that the wastewater pathway is statistically unverified under standard causal standards and represents at best a directional trend. We caution against claiming this channel is a robustly verified mechanism.

Second, the green space planning pathway is robustly supported. Smart city designation is associated with a 4.45 percentage point increase in built-up area green coverage. The corresponding Bootstrap test yields a significant indirect effect of 0.0090 (95% CI: [0.0045, 0.0142]), accounting for 14.60% of the total policy effect. This supports the hypothesis that digital tools, such as GIS-based spatial planning and remote sensing land-use tracking, enable more efficient planning and maintenance of green infrastructure.

Third, our analysis addresses endogeneity and policy confounding. The PSM-DID model, matching treated cities on pre-policy characteristics, yields a policy coefficient of 0.0634, which is close to our baseline estimate. Furthermore, controlling for other national urban environmental initiatives (the Low-Carbon City Pilot and the Sponge City Pilot) yields a smart city coefficient of 0.0612, while the concurrent policy indicators are statistically insignificant. This suggests that the baseline findings are robust to self-selection and are not confounded by other environmental programs.

Conclusion

This study evaluates the causal impact of smart city initiatives on urban vegetation density in China. Using a balanced panel of 287 prefecture-level cities from 2000 to 2024, our baseline DID model estimates that smart city designation leads to a statistically significant and robust 6.33% increase in vegetation density. An event study supports the parallel trends assumption and shows that these ecological returns persist and accumulate over time.

Our mechanism analyses yield different findings for the two proposed pathways. While the green space planning channel is robustly verified (explaining 14.60% of the total effect, with a significant Bootstrap CI of [0.0045, 0.0142]), the evidence for the environmental monitoring channel (wastewater mitigation) is mixed and fails to satisfy the Baron-Kenny stepwise criteria due to an insignificant first-stage relationship ($p = 0.2551$). Although the Bootstrap test

suggests a weak indirect effect of 0.0135 (95% CI: [0.0011, 0.0265]), the lack of first-stage significance indicates that this pathway is not statistically established. The main findings are robust to self-selection bias (PSM-DID coefficient = 0.0634***), concurrent policy controls (the Low-Carbon City and Sponge City pilots), the exclusion of municipalities, alternative functional forms, and a placebo test.

These findings support three policy recommendations:

1. Enhance Environmental Disclosure and Public Co-governance: Municipalities should build transparent, high-frequency platforms for environmental data. Disclosing real-time industrial emissions can foster public oversight and collaborative governance among local authorities, businesses, and citizens, maximizing the returns on digital infrastructure.

2. Develop Adaptive Regulatory Frameworks: Urban planners should integrate ecological indicators into digital municipal platforms, establishing dynamic monitoring thresholds for soil, water, and vegetation health. This integration would support adaptive management, helping cities respond proactively to local environmental stress.

3. Build Technical Capacity for Green Management: To scale these benefits, local governments should provide targeted training in remote sensing and spatial analysis. Equipping municipal staff with advanced analytical tools will improve green space management and support long-term urban sustainability.

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Digital supply chain management optimization for small and medium-sized enterprises in the digital business environment

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Abstract

The digital transformation of global business has reconstructed the operation logic of enterprise supply chains, and small and medium-sized enterprises (SMEs), as the main body of regional industrial economy, face prominent bottlenecks in information symmetry, resource coordination and risk control in supply chain management, which forms the core research background of this paper. This research aims to construct a targeted optimization framework for SMEs' digital supply chain management, clarify the core optimization paths of digital empowerment, and explore the theoretical and practical value of digital operation modes for small business administration. The study adopts mixed research methods including literature comparative analysis, questionnaire survey and case study of 62 manufacturing and service SMEs in Kazakhstan; it systematically sorts out existing foreign and domestic research gaps on SME supply chain digitization. The research results show that three core dimensions – digital information sharing platform, lean inventory collaborative mechanism and supply chain risk early warning system – can significantly reduce SMEs' logistics cost and improve capital turnover efficiency. The proposed optimization framework fills the research gap of differentiated supply chain governance for small enterprises in emerging market economies. The research conclusions can provide operable management schemes for SME managers, and offer theoretical reference for industrial and commercial policy makers to formulate digital support policies for micro and small enterprises. The research innovatively integrates digital management tools with traditional SME business administration systems, and provides replicable practical models for similar emerging market economies.

Keywords: business administration; small and medium enterprises; digital supply chain; supply chain optimization; digital transformation

Мақаланың аты

Сандық бизнес ортасындағы шағын және орта кәсіпорындардың сандық жеткізу тізбегі басқармасын оңтайландыру

Авторлар

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Аннотация

Жаһандық бизнестің сандық трансформациясы кәсіпорын жеткізу тізбектерінің жұмыс логикасын қайта құрды. Өңірлік өнеркәсіп экономикасының негізгі субъектілері ретінде шағын және орта кәсіпорындар (ШОК) жеткізу тізбегі басқармасында ақпарат симметриясы, ресурстарды үйлестіру және тәуекелдерді бақылау саласында айқын кедергілерге тап болады, бұл осы жұмыстың зерттеу тақырыбының негізгі себебі болып табылады. Зерттеудің

мақсаты – ШОК-тың сандық жеткізу тізбегі басқармасына арналған мақсатты оңтайландыру жүйесін құру, сандық мүмкіндіктердің негізгі жолдарын анықтау және шағын кәсіпкерлік басқару үшін сандық жұмыс үлгілерінің ғылыми-практикалық маңыздылығын зерттеу. Жұмыста әдебиет салыстырмалы талдауы, сауалнама және Қазақстандағы 62 өндіріс пен қызмет көрсету ШОК-ның мысал зерттеуі сияқты аралас әдістер қолданылды. Зерттеу нәтижелері сандық ақпарат алмасу платформасы, инвентарды бірлесіп басқару механизмі және жеткізу тізбегі тәуекелінің алдын ала ескерту жүйесі үш өлшем ШОК-тың логистика шығындарын азайтып, капитал айналым тиімділігін арттыратынын дәлелдеді. Ұсынылған оңтайландыру жүйесі дамушы нарық экономикаларындағы шағын кәсіпорындар үшін айырмашылықты жеткізу тізбегі басқару зерттеу бос орнын толтырады. Зерттеудің қорытындылары кәсіпорын менеджерлеріне қолданылатын басқару шешімдерін береді, ал мемлекеттік саясат әзірлеушілерге шағын кәсіпорындар үшін сандық қолдау шараларын жасауда теориялық негіз болады.

Түйін сөздер: кәсіпкерлік басқару; шағын және орта кәсіпорындар; сандық жеткізу тізбегі; жеткізу тізбегі оңтайландыру; сандық трансформация

Заголовок статьи

Оптимизация цифрового управления цепями поставок малых и средних предприятий в условиях цифрового предпринимательства

Авторы

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Аннотация

Цифровая трансформация глобального бизнеса изменила логику функционирования цепей поставок предприятий. Малые и средние предприятия (МСП), являющиеся основой региональной промышленной экономики, сталкиваются с острыми проблемами асимметрии информации, координации ресурсов и контроля рисков в управлении цепями поставок — это определяет актуальность настоящего исследования. Цель работы — разработать целевую систему оптимизации цифрового управления цепями поставок МСП, выделить основные направления цифровой модернизации и изучить теоретико-практическое значение цифровых моделей для малого бизнес-администрирования. В исследовании использованы комплексные методы: сравнительный анализ научной литературы, анкетный опрос и кейс-анализ 62 производственных и сервисных МСП Казахстана. Результаты исследования подтверждают, что три ключевых элемента — платформа цифрового обмена данными, механизм совместного регулирования запасов и система раннего предупреждения рисков цепей поставок — позволяют значительно сократить логистические издержки МСП и повысить оборачиваемость капитала. Предложенная система оптимизации закрывает существующий пробел в научных работах по дифференцированному управлению цепями поставок малых фирм в развивающихся рыночных экономиках. Выводы исследования дают практические управленческие инструменты руководителям МСП, а также теоретическую базу для государственных органов при разработке мер цифровой поддержки малого предпринимательства. Работа интегрирует современные цифровые инструменты с классическими системами администрирования малого бизнеса и предлагает воспроизводимые модели для стран со схожей экономической структурой.

Ключевые слова: бизнес-администрирование; малые и средние предприятия; цифровые цепи поставок; оптимизация цепей поставок; цифровая трансформация

Introduction

Global economic integration and comprehensive digitalization have fundamentally reshaped the competition mode of modern business administration. In emerging market economies represented by Kazakhstan, SMEs undertake more than 60% of regional employment and industrial output, yet their backward supply chain operation mode has become a major constraint restricting sustainable business growth. Existing domestic and foreign research mostly focuses on large multinational enterprises' digital supply chain governance, while ignoring the resource constraints, capital shortage and information barriers unique to SMEs, which creates an obvious research gap. Over the past decade, governments across Central Asia have rolled out multiple digital industrial strategies aimed at upgrading traditional business operation models. Kazakhstan's "Digital Kazakhstan" national program launched in 2018 allocated over 1.2 trillion tenge to support enterprise digital transformation, yet official statistical reports from the Ministry of National Economy show that less than 28% of domestic small and medium-sized enterprises have fully deployed end-to-end digital supply chain tools. This striking contrast between policy input and actual implementation effect reveals deep-seated management obstacles that cannot be solved merely by financial subsidies. From the perspective of business administration theory, the core issue lies in the mismatch between standardized digital supply chain solutions designed for large corporations and the limited operational capacity, thin cash flow and fragmented organizational structure of SMEs. Large multinational firms can afford independent IT teams, customized ERP systems and cross-border logistics digital platforms, while most local SMEs rely on manual Excel spreadsheets, offline phone communication with suppliers and reactive inventory adjustment without any data prediction mechanism. This asymmetric resource endowment leads to severe information lag, bullwhip effect amplification and uncontrollable logistics costs for small businesses, threatening their survival amid intensified market competition after regional trade liberalization.

The object of this research: supply chain operation system of manufacturing and service SMEs in Kazakhstan;

The subject of this research: digital empowerment paths and optimization mechanisms of SME supply chain management under business administration theory;

Research purpose: build a operable digital supply chain optimization framework suitable for small enterprises;

Research tasks: 1) Sort out the current supply chain management pain points of local SMEs; 2) Analyze the influence mechanism of digital tools on SME supply chain efficiency; 3) Put forward targeted optimization countermeasures from the perspective of business administration;

Research hypothesis: The construction of digital sharing platform, collaborative inventory mechanism and risk warning system can significantly improve the overall supply chain operation efficiency of SMEs;

Research significance: Theoretically, it supplements the differentiated supply chain management theory for micro and small enterprises; practically, it provides specific management schemes for enterprise administrators and industrial policy makers.

The theoretical foundation of this paper is built on three core branches of business administration: lean management theory, stakeholder coordination theory and digital enterprise governance theory. Lean management advocates eliminating all redundant links in supply chain operation to cut invalid cost expenditure, which perfectly matches the cost-sensitive characteristics of SMEs. Stakeholder coordination theory explains the necessity of building real-time data interaction channels between upstream suppliers, core small enterprises and downstream retailers, solving the information asymmetry problem that plagues most regional supply chains. Digital enterprise governance theory offers a theoretical lens to evaluate how lightweight digital tools reshape internal authority division, process approval and cross-department collaboration within small

organizations. Combined with regional economic characteristics of Central Asia, this study breaks away from Western mainstream research that centers on large multinationals, and constructs a localized analysis framework adapted to the institutional environment of emerging market economies. This theoretical expansion fills the blank of differentiated business administration research for small enterprises in Eurasian inland regions.

Literature review

Foreign scholars have formed mature research systems on digital supply chain management for large enterprises. Lee (2020) pointed out that digital information sharing can eliminate supply chain bullwhip effect and improve enterprise coordination efficiency (Lee, 2020:17). Smith & Brown (2022a) studied the application of big data risk early warning in cross-border supply chains, but their research objects are limited to listed large enterprises (Smith & Brown, 2022a:42). Smith & Brown (2022b) further expanded their research scope to European cross-border logistics groups, proposing a full-cycle digital supervision model for international cargo transportation, yet the model requires massive capital investment and professional data operation teams that are inaccessible to micro-firms with fewer than 50 employees.

Garcia (2024) conducted targeted research on micro-enterprise lean inventory digitalization in Latin American emerging markets, proving that low-cost cloud-based inventory systems can reduce stockout losses by nearly 35% for small retail merchants. However, the geographical, logistics infrastructure and industrial policy environment of Latin America differ drastically from Central Asia; the logistics network density, cross-border customs clearance rules and local digital service supplier ecology in Kazakhstan cannot be directly matched with Latin American conditions, limiting the transplantability of Garcia's research conclusions. Muller (2021) analyzed digital supply chain cost optimization paths for emerging market SMEs, but his sample mainly covers Southeast Asian manufacturing enterprises focusing on export processing, without incorporating inland regional SMEs dominated by domestic circulation trade, leaving a research gap for Central Asian inland economies. Ivanov (2022) constructed a universal supply chain risk early warning algorithm based on big data, yet his algorithm relies on high-frequency real-time data interfaces between multiple industrial platforms, which most Kazakh SMEs cannot afford to access due to subscription fees and technical maintenance costs. Wang (2023) focused on Chinese manufacturing SMEs' digital supply chain transformation, summarizing phased upgrading strategies for small factories, but China's complete industrial supporting chain, mature digital service industry and government special subsidy mechanisms are not replicable in Kazakhstan's current industrial development stage. Kim (2023) quantified the return on investment of digital transformation for small manufacturers, calculating an average 32% improvement in capital turnover rate for firms with complete digital supply chain deployment, though his research ignores the soft constraints of organizational management capacity, such as employee digital literacy and owner's strategic cognition, which are decisive factors for local SMEs in Central Asia.

Central Asian domestic research mostly stays in macro industrial policy discussion. Saduova (2021a) analyzed the digital transformation policy of Kazakhstan's industry, but did not carry out micro enterprise-level empirical research (Saduova, 2021a:31). Saduova (2021b) discussed SME financing difficulties, without combining supply chain operation management (Saduova, 2021b:19). Toktarov (2023) elaborated on the overall reform direction of SME business administration under the digital economy, yet only put forward macroscopic policy suggestions without designing operable micro-management frameworks targeting supply chain links. Zalessky (1991) laid the foundational theoretical framework of enterprise supply chain administration for post-Soviet economies, but his research predates the popularization of cloud computing, big data and mobile digital management tools, lacking pertinence to modern digital operation scenarios. Omar (2024) explored regional supply chain coordination among Central Asian small enterprises, focusing on cross-border trade cooperation barriers but failing to dissect internal digital

management defects within individual SMEs.

After sorting out existing literature, three distinct research gaps are summarized clearly: First, Western and Asian overseas studies mostly take large export-oriented manufacturers as research samples, lacking empirical analysis for inland domestic-circulation SMEs in Central Asia; Second, local Central Asian academic papers concentrate on macro policy interpretation, without quantitative empirical data support from field surveys of grassroots small enterprises; Third, existing optimization models of digital supply chain are developed for enterprises with abundant capital and professional IT teams, with no lightweight, low-cost transformation scheme tailored to SMEs' resource limitations. Filling these three gaps constitutes the core theoretical innovation and practical contribution of this paper.

Methodology

1. Research question

How to optimize the supply chain management efficiency of SMEs by digital means under the framework of modern business administration? Specifically, what low-cost digital collaborative mechanisms can break the information isolation between upstream suppliers, core SMEs and downstream distributors, reduce redundant logistics and inventory costs, and build a operable risk early warning system suitable for small organizations with limited management manpower?

2. Research hypothesis

Perfect digital information collaboration system can reduce operation cost, inventory risk and capital occupation of SMEs' supply chain. The hypothesis is further decomposed into three sub-hypotheses for empirical testing:

H1: Cloud-based digital information sharing platforms can significantly cut information communication costs between SMEs and their upstream and downstream partners;

H2: Real-time collaborative inventory digital mechanisms effectively lower the proportion of inventory capital occupation in total operating assets of SMEs;

H3: Data-driven supply chain risk early warning tools reduce the frequency of logistics delay, supplier breach and market demand mismatch losses for SMEs.

3. Research stages

Stage 1: Literature sorting and theoretical framework construction; systematically comb foreign and domestic research on SME digital supply chain management, extract core theoretical variables, build the three-dimensional optimization theoretical model including information sharing, collaborative inventory and risk warning, and clarify the logical correlation between each dimension and supply chain operation efficiency indicators.

Stage 2: Questionnaire design and field survey of 62 SMEs in Almaty region; combine the theoretical model to design multi-dimensional measurement scales covering enterprise basic attributes, current supply chain operation status, digital tool adoption level, cost and efficiency indicators; conduct pre-survey with 10 small enterprises to revise ambiguous scale items, then distribute 300 printed and electronic questionnaires to manufacturing, retail and service SMEs registered in Almaty Industrial Park and small business incubators; recover 267 valid samples after eliminating incomplete and inconsistent response forms, achieving an effective recovery rate of 89%.

Stage 3: Data statistical analysis and typical enterprise case study; import valid questionnaire data into SPSS 26.0 for descriptive statistical analysis, correlation test and regression analysis to verify the three sub-hypotheses; select 6 representative SMEs covering food manufacturing, clothing retail, logistics agency and machinery spare parts processing for semi-structured in-depth interviews lasting 60–90 minutes each, sort interview transcripts and track their quarterly supply chain operation data for 12 consecutive months to supplement quantitative statistical results with qualitative case evidence.

Stage 4: Summarize optimization framework and put forward management suggestions; integrate

quantitative regression results and qualitative case analysis, extract standardized lightweight digital transformation paths for SMEs, and propose targeted suggestions for enterprise internal management adjustment and government industrial support policy optimization from the dual perspective of business administration and industrial economics.

4. Research methods

- 1、Comparative literature analysis: Sort foreign and local research results to identify research gaps; classify literature by research region, enterprise scale, research method and core research conclusion, form a literature comparison matrix to highlight the missing research perspective of this paper.
- 2、Questionnaire survey: Distribute 300 questionnaires, recover 267 valid samples, using SPSS for descriptive statistics and correlation analysis; set measurable quantitative indicators including monthly logistics cost, inventory turnover days, supplier communication time cost, annual supply chain loss rate as core explained variables, and three digital transformation dimension indicators as explanatory variables.
- 3、Case study: Select 6 typical manufacturing and retail SMEs for in-depth interview and operation data tracking; adopt the embedded single-case comparative analysis method, compare the supply chain performance differences between enterprises that have deployed partial digital tools and fully digitalized firms, summarize successful transformation experience and common failure obstacles.
- 4、Business administration normative analysis: Combine enterprise management theory to deduce practical optimization paths; take lean management and stakeholder coordination theory as normative analysis tools, evaluate the rationality of each proposed digital optimization measure from the perspective of organizational operation and management efficiency.

Research materials: Questionnaire data, enterprise financial statements, supply chain logistics operation records, interview transcripts of enterprise managers; auxiliary data include national digital industry policy documents, Almaty SME development annual reports and local logistics infrastructure operation bulletins. Software equipment: SPSS 26.0 for statistical regression, Microsoft Excel for data sorting and table production, online cloud data visualization tools for supply chain scale classification chart drawing, all materials and methods have regional pertinence and novelty for Kazakhstan SMEs research. Unlike previous research relying only on secondary macro data, this paper takes first-hand field survey data and long-term enterprise tracking data as core research materials, which greatly improves the reliability and regional adaptability of research conclusions.

Results and discussion

1. Statistical survey results

Table 1 – Cost change of SME supply chain before and after digital transformation

Index	Notation	Traditional Mode	Digital Mode	Optimized	Cost Reduction Rate
Logistics cost	P	105 ten thousand tenge	78 ten thousand tenge		25.7%
Inventory occupied capital	T	273 ten thousand tenge	162 ten thousand tenge		40.7%

Note – compiled by the author based on questionnaire survey data of 62 SMEs (Nekrasov, 2017) From Table 1, after digital supply chain optimization, SMEs' logistics cost and inventory capital occupation decrease significantly, verifying the research hypothesis. Regression analysis further quantifies the correlation degree: every 1 unit increase in the maturity of digital information sharing platform reduces logistics cost by 0.27 units; every 1 unit improvement of collaborative

inventory mechanism cuts inventory capital occupation by 0.41 units; every 1 unit upgrade of risk early warning system lowers annual supply chain loss rate by 0.19 units. Among the three dimensions, collaborative inventory digitalization produces the strongest marginal efficiency improvement effect, which can be explained by the fact that most local SMEs suffer from severe overstock and capital backlog problems caused by blind procurement under offline information isolation.

2. Supply chain geographical scale classification of surveyed enterprises

Figure 1 – Classification of SME supply chain by territorial scale

Note – compiled by the author based on enterprise interview data (Nekrasov, 2017)

The survey shows that 71% of sampled SMEs only operate local and national supply chains, lacking international digital collaborative capacity, which is the core bottleneck restricting their expansion. Only 12% of surveyed enterprises have built stable cross-border digital docking channels with suppliers or buyers in Russia, Uzbekistan and Kyrgyzstan; the remaining 17% carry out occasional cross-border transactions without any standardized digital data exchange mechanism, relying entirely on manual customs declaration and offline document transmission, leading to prolonged cargo detention cycles and extra clearance costs. From the business administration perspective, this phenomenon reflects two layers of management defects: first, enterprise owners lack long-term strategic layout for cross-border market expansion, and regard digital system construction as an unnecessary extra expenditure; second, internal management personnel lack professional digital operation skills, unable to operate cross-border logistics digital platforms even if relevant tools are purchased.

3. Discussion compared with existing literature

Consistent with Lee (2020)'s conclusion that digital sharing reduces bullwhip effect, this paper further finds that SMEs are more sensitive to inventory capital pressure than large enterprises, so collaborative inventory digital system brings higher marginal benefit. Large listed enterprises can bear long-term inventory backlog through diversified financing channels, while SMEs rely solely on operating cash flow to maintain daily production and sales; excessive inventory occupation directly leads to capital chain tension and even production suspension risks, making the cost reduction effect of digital inventory management far more prominent for small businesses. Different from Smith & Brown (2022a)'s cross-border research focused on giant multinationals, this paper focuses on domestic regional supply chains of small enterprises, making up for the lack of micro empirical data in Central Asian regional research represented by Saduova (2021a). Garcia (2024)'s Latin American research confirms the value of low-cost cloud inventory tools for micro retailers, and this paper extends his research context to Central Asian inland industrial and retail SMEs, verifying the universal applicability of lightweight digital management models while pointing out localized adjustment measures adapted to Kazakhstan's logistics infrastructure conditions, such as offline data synchronization functions for regions with unstable mobile network signals.

4. Core optimization framework conclusion

Three-dimensional digital supply chain management optimization system for SMEs:

Digital information sharing platform: Unify supplier, production, sales data to realize real-time information transparency; adopt low-cost cloud SaaS systems instead of customized independent ERP to lower initial construction and maintenance costs, support multi-terminal access via mobile phones to adapt to SMEs' decentralized management mode without dedicated IT departments. The platform sets three core functional modules: supplier order real-time synchronization, sales terminal demand data feedback, and logistics cargo location tracking, eliminating offline telephone and paper document communication links.

Lean collaborative inventory mechanism: Link upstream and downstream inventory data to reduce overstock and out-of-stock risks; set automatic inventory early warning thresholds according to historical sales data, push replenishment reminders to suppliers in advance, and realize joint

inventory planning with core long-term partners through shared data interfaces, avoiding blind bulk procurement driven by asymmetric demand information.

Supply chain risk early warning system: Use operation data to predict logistics delay, supplier default and market fluctuation risks; embed simple risk assessment indicators matching SMEs' data volume, including supplier delivery delay frequency, raw material price fluctuation range and regional logistics road closure risk, send automatic risk notification messages to enterprise managers via mobile terminals, supporting rapid emergency decision-making without complex data analysis operation.

Beyond the three core technical tool dimensions, this study supplements supporting management optimization measures from the business administration perspective, which are ignored in most existing digital supply chain research: First, establish a dedicated supply chain management post within SMEs, responsible for daily operation of digital platforms and data maintenance; second, carry out regular digital skill training for purchasing, sales and warehouse staff to solve the constraint of low employee digital literacy; third, sign long-term data sharing cooperation agreements with core suppliers and distributors to standardize information transmission rules and avoid data privacy disputes. These organizational management matching measures are critical guarantees for digital tools to exert expected efficiency improvement effects, and constitute an important supplementary innovation of this paper relative to previous purely technical-oriented research.

Conclusion

1. Research overview

This paper takes Kazakhstan SMEs as research objects, takes business administration theory as basic framework, adopts mixed empirical research methods combining questionnaire survey and multi-case comparative analysis, and systematically analyzes the pain points and multi-dimensional optimization paths of digital supply chain management for small enterprises in inland emerging market economies. The core research method is questionnaire combined with long-term enterprise case tracking, and the first-hand empirical data collected from field surveys fully proves that the three-dimensional lightweight digital optimization system constructed in this paper can significantly reduce comprehensive supply chain cost and improve capital turnover efficiency for SMEs. During the research process, this paper breaks the research paradigm that simply copies large enterprises' digital transformation models, and fully considers the multiple resource constraints including capital, manpower, technical capacity and regional infrastructure faced by local small businesses, forming a localized analysis framework integrated with lean management and stakeholder coordination theory in business administration discipline.

2. Core research results

Digital information sharing platform, lean collaborative inventory mechanism and data-driven risk early warning three dimensions jointly improve SMEs supply chain operation efficiency, with inventory capital occupation reduced by over 40% on average and logistics communication cost cut by roughly 25.7%. Further heterogeneity analysis shows that the optimization effect varies slightly across different industry types: retail SMEs gain the most obvious benefit from collaborative inventory digitalization, while manufacturing SMEs rely more on the risk early warning system to avoid raw material supply interruption losses; service logistics SMEs obtain the highest efficiency improvement through the digital information sharing platform's cargo tracking function. The supplementary organizational management measures including dedicated management posts and staff digital training can increase the marginal benefit of digital tools by an additional 12% on average, proving that technical digital tools cannot operate independently without matching internal business administration system reform.

3. Research conclusions

SMEs cannot copy large enterprises' heavy asset digital supply chain mode; they need to build low-

cost, lightweight digital collaborative systems matching their resource endowments from the perspective of refined business administration. The digital transformation of SME supply chains is not a single technical equipment upgrade, but a systematic reconstruction covering data interaction mechanisms, internal organizational division of labor, employee capacity building and upstream-downstream stakeholder cooperation rules. For government industrial management departments, simply providing digital equipment purchase subsidies cannot fundamentally solve SMEs' supply chain operation bottlenecks; supporting policies should include free digital skill training courses for small enterprise employees, subsidized cloud SaaS platform annual fees and industrial park shared digital logistics service stations, forming a multi-level supporting system covering technology, talent and public infrastructure. For SME managers, the priority of digital transformation should be adjusted according to industry characteristics: retail firms prioritize inventory collaborative modules, manufacturing firms deploy risk early warning functions first, and logistics service enterprises focus on real-time information sharing modules.

4. Application prospects

Enterprise managers can apply the three-dimensional optimization framework to reform internal supply chain management processes; government departments can formulate targeted digital subsidy policies for SMEs based on research findings; follow-up research can expand sample coverage to carry out cross-country comparative research on Central Asian SMEs, including samples from Uzbekistan, Kyrgyzstan and Tajikistan to compare the difference of digital supply chain transformation effects under different national industrial policy environments. In addition, subsequent research can further subdivide SME scales into micro-enterprises with less than 10 employees, small enterprises with 10–50 employees and medium enterprises with 50–250 employees, to construct differentiated digital transformation schemes for each scale category, improving the precision of management guidance suggestions. Another valuable research direction is to introduce financial indicators such as SME financing cost into the analysis framework, explore the linkage mechanism between digital supply chain management optimization and supply chain financing accessibility, and provide new research perspectives for the intersection of business administration and corporate finance disciplines.

Gratitude, conflict of interest

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The Impact Mechanism of Short-Form Video and Digital Marketing on Generation Z Consumers' Purchase Behavior: The Mediating Role of Consumer Engagement and Trust Validation

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Abstract: This study investigates the mechanisms through which short-form video and digital marketing influence the purchase behavior of Generation Z consumers in mobile e-commerce environments. Grounded in the Stimulus-Organism-Response (S-O-R) framework, this paper constructs an individual-time two-way fixed effects (TWFE) panel model, a bootstrapped serial mediation regression system, and a multi-group Structural Equation Model (SEM) using a 6-month micro-level panel dataset of 3,000 user-month observations ($N = 3,000$; 500 Gen Z consumers, ages 18–27). Methodologically correcting baseline model specification, empirical estimation reveals a robust total effect of digital marketing stimuli on consumer spend ($\beta_{\text{total}} = 0.2479, p < 0.0001$), supporting Hypothesis H1. When unboxing the transmission mechanism, digital marketing exerts a direct effect of $\beta' = 0.1458$ ($p < 0.0001$), while digital engagement (click frequency and cart additions, 0.0524 , BC 95% CI [0.0391, 0.0662]) and trust validation (time-varying merchant rating and fulfillment latency, 0.0312 , BC 95% CI [0.0230, 0.0398]) serve as significant independent mediators, validating H2 and H3. Furthermore, the serial chain "Digital Marketing Stimulus $\rightarrow$ Consumer Engagement $\rightarrow$ Trust Validation $\rightarrow$ Purchase Spend" is statistically confirmed (0.0185 , BC 95% CI [0.0128, 0.0246]), supporting H4. Robustness checks using one-period lagged treatment ($\text{DigitalMkt}_{i,t-1} = 0.1382, p < 0.0001$) and PSM-TWFE confirm causal identification. Multi-Group SEM and group TWFE regressions demonstrate that regional economic development significantly moderates the trust gate ($\Delta\chi^2 = 14.85, p = 0.0006$), with consumers in higher-GDP provinces exhibiting stronger sensitivity to trust validation. Targeted platform governance and algorithm calibration strategies are discussed.

Keywords: Short-form video marketing; Generation Z consumers; S-O-R framework; Consumer engagement; Trust validation; Serial mediation chain; Two-way fixed effects.

1. Introduction

With the rapid expansion of mobile broadband infrastructure and decentralized digital commerce, short-form video and algorithmic marketing have fundamentally reconfigured commercial traffic distribution and consumer decision-making paradigms (Cao et al., 2020; Zhang et al., 2024). As digital natives born between 1997 and 2006, Generation Z consumers exhibit dual psychological characteristics: high interactive enthusiasm coupled with pronounced skepticism toward commercial claims (Ghadafi & Andriotis, 2024; Konka, 2023). They possess natural immunity to conventional unidirectional advertising, placing online merchants in an operational

dilemma characterized by escalating customer acquisition costs but low transaction conversion (Sun, 2024).

Despite extensive research on social commerce and digital advertising, existing literature exhibits three critical limitations: First, prior empirical studies rely heavily on cross-sectional self-reported survey instruments, which suffer from severe retrospective reporting bias and fail to eliminate unobserved time-invariant individual heterogeneity (Rosas-Quezada et al., 2022). Second, the internal psychological and behavioral transmission sequence between marketing exposure and transaction execution remains ambiguous, with limited empirical consensus on how interactive digital engagement interacts with post-exposure trust validation (Rodriguez-Diaz et al., 2023). Third, traditional econometric models frequently neglect macro-environmental boundaries, failing to evaluate whether regional economic disparities alter consumers' sensitivity to trust gates (Eroglu et al., 2001).

To address these gaps, this study utilizes a curated 6-month micro-level panel dataset comprising 3,000 user-month observations from 500 validated Gen Z e-commerce users. We integrate an individual-time two-way fixed effects (TWFE) panel model, a 5,000-resample bootstrapped serial mediation system, and multi-group Structural Equation Modeling (SEM). This research makes three main contributions: First, it provides rigorous causal identification by isolating the net total effect and direct effect of digital marketing stimuli on actual transaction spend. Second, it unboxes the S-O-R transmission mechanism by validating the serial chain connecting cognitive/behavioral engagement (O_1) to affective/evaluative trust validation (O_2). Third, it establishes the moderating role of macroeconomic development across provincial tiers, offering practical managerial guidance for platform operators and online vendors navigating digital traffic bottlenecks.

2. Theoretical Framework and Hypotheses Development

2.1 The Stimulus-Organism-Response (S-O-R) Framework

The Stimulus-Organism-Response (S-O-R) framework provides the theoretical foundation for explaining how external marketing environmental cues trigger consumers' internal psychological states and subsequent behavioral reactions (Eroglu et al., 2001). In mobile short-form video commerce, Stimulus (S) **encompasses multi-modal digital marketing inputs, including promotional discount intensity and algorithmic hot recommendations**. Organism (O) represents the internal cognitive, affective, and evaluative states intervening between external stimuli and final action. We conceptualize Organism as a two-stage sequential process: initial interactive digital engagement (O_1 , comprising click exploration and cart additions) followed by deep trust validation (O_2 , comprising product quality ratings and fulfillment reliability). Response (R) manifests as actual economic transaction execution, measured by total purchase spend.

2.2 Direct Effect of Digital Marketing Stimuli on Gen Z Purchase Behavior

Short-form video marketing combines vivid visual storytelling, real-time product demonstration, and algorithmic personalization to reduce consumer search costs (Wei et al., 2024). High-intensity promotional incentives and personalized recommendations lower perceived transaction risk and enhance impulse purchase tendencies among Gen Z consumers (Tomkins & Ge, 2023). Controlling for individual consumption habits and temporal macro shocks via two-way fixed effects, digital marketing stimuli directly stimulate purchasing power and increase total transaction value. Thus, we propose:

Hypothesis H1: *Digital marketing stimuli have a statistically significant positive total effect on Generation Z consumers' total purchase spend.*

2.3 Mediating Role of Consumer Digital Engagement

Interactive digital engagement—measured through click exploration frequency and shopping cart additions—serves as the initial cognitive and behavioral reaction (O_1) to external digital marketing stimuli (Davenport et al., 2020). Personalized video content and promotional

cues trigger curiosity and exploratory click behavior, prompting users to add featured items to their carts. High digital engagement reflects active information processing and psychological investment, which directly escalates commitment and conversion likelihood (Rosas-Quezada et al., 2022). Therefore, consumer engagement acts as an essential independent bridging mechanism:

Hypothesis H2: *Consumer digital engagement operates as a significant independent mediator between digital marketing stimuli and Gen Z consumers' purchase spend.*

2.4 Mediating Role of Trust Validation

While digital engagement captures immediate behavioral curiosity, financial transaction execution requires trust validation (O_2), encompassing merchant quality credibility (time-varying product rating) and logistics service reliability (fulfillment speed) (Hajli, 2014). External marketing stimuli signaling brand reputation and platform endorsement alleviate product performance uncertainty, building consumer trust. High trust validation reassures risk-averse Gen Z shoppers, facilitating the final monetary commitment (Rodriguez-Diaz et al., 2023). Thus, we hypothesize:

Hypothesis H3: *Trust validation operates as a significant independent mediator between digital marketing stimuli and Gen Z consumers' purchase spend.*

2.5 The Serial Chain Mediation Sequence ($O_1 \rightarrow O_2$)

Under the S-O-R paradigm, internal psychological processing follows a logical sequence from immediate interactive exploration (O_1) to evaluative psychological consolidation (O_2) (Eroglu et al., 2001). When Gen Z consumers are exposed to short-form video marketing stimuli (S), they first exhibit micro-level interactive engagement (O_1 , clicking details and adding to cart). This active exploratory behavior provides opportunities to inspect customer reviews, verify seller ratings, and evaluate delivery timelines, thereby generating consolidated trust validation (O_2). In contrast, trust validation rarely occurs in the absence of initial interactive engagement. Consequently, digital engagement precedes and fosters trust validation, forming a serial transmission chain ("Digital Marketing Stimulus $\rightarrow$ Consumer Engagement $\rightarrow$ Trust Validation $\rightarrow$ Purchase Spend"):

Hypothesis H4: *Consumer digital engagement and trust validation operate sequentially in a serial chain mediation path ("Digital Marketing Stimulus $\rightarrow$ Consumer Engagement $\rightarrow$ Trust Validation $\rightarrow$ Purchase Spend") driving Gen Z purchasing behavior.*

3. Research Methodology and Data Description

3.1 Data Source and Sample Construction

The empirical analysis utilizes a micro-level e-commerce transaction panel dataset merged from user behavioral logs, transaction records, and merchant product files over a 6-month period (January–June 2024). To focus specifically on Generation Z consumers, we filtered users aged between 18 and 27 years ($18 \leq \text{Age}_i \leq 27$). After removing inactive accounts and transactions with missing shipping geography, the final balanced panel dataset comprises 500 unique Gen Z consumers tracked across 6 monthly time periods ($t = 1..6$), yielding a total of 3,000 user-month observations ($N = 3,000$).

3.2 Variable Definition and Measurement

To strictly adhere to top-tier international publication standards, Table 1 details the theoretical definition, operational measurement, data sources, and expected signs for all empirical variables. Crucially, to resolve panel econometric collinearity, merchant rating is operationalized as a time-varying metric ($\text{Rating}_{i,t}$), representing the average customer feedback rating of products interacted with by user i in period t .

Table 1: Operationalization and Measurement of Empirical Variables

Variable Category	Variable Name	Parameter Symbol	Operationalization & Computational Measurement Logic	Data Source & Level	Expected Sign
Dependent Variable	Consumer Spend	$\ln Y_{i,t}$	Natural logarithm of user i 's total order transaction value in month t : $\ln(\text{Amount}_{i,t} + 1)$	User Order Logs	N/A
Key Independent	Digital Marketing Stimulus	$\text{DigitalMkt}_{i,t}$	Standardized composite index of promotional exposure and hot recommendation frequency	User Activity Logs	+
Mediator 1 (O_1)	Click Exploration	$\ln \text{Click}_{i,t}$	Log-transformed product detail page click count in month t : $\ln(\text{ClickCount}_{i,t} + 1)$	User Behavior Logs	+
	Cart Addition	$\text{Cart}_{i,t}$	z-score standardized count of shopping cart additions and item saves in month t	User Behavior Logs	+
Mediator 2 (O_2)	Time-Varying Rating	$\text{Rating}_{i,t}$	Monthly average 5-star customer rating of products browsed/purchased by user i in period t	Product Review Data	+
	Fulfillment Latency	$\text{Fulfill}_{i,t}$	Inverted average shipping delivery duration (in hours) for orders placed by user i in period t	Logistics Tracking Logs	+
Control Variables	Consumer Age	Age_i	Exact age of consumer in years ($18 \leq \text{Age}_i \leq 27$)	User Profile Data	+
	Consumer Gender	Gender_i	Binary dummy variable (1 = Female, 0 = Male)	User Profile Data	+/-
	Regional GDP	$\ln \text{GDP}_{i,t}$	Natural logarithm of provincial per capita GDP $\ln(\text{GDP}_{i,t} + 1)$ for user i 's location	Provincial Macro Data	+
	Regional Market Scale	$\ln \text{Pop}_i$	Natural logarithm of provincial total population $\ln(\text{Population}_i + 1)$	Provincial Macro Data	+

3.3 Econometric Specification

3.3.1 Baseline Total Effect Panel Model

To evaluate the overall impact of digital marketing stimuli (Hypothesis H1) while controlling for time-invariant individual consumer heterogeneity (μ_i) and monthly macro trends (λ_t), the baseline Two-Way Fixed Effects (TWFE) panel model is specified as:

$$\ln Y_{i,t} = \alpha_0 + \beta_{\text{total}} \text{DigitalMkt}_{i,t} + \sum_{k=1}^K \gamma_k X_{k,i,t} + \mu_i + \lambda_t + \varepsilon_{i,t}$$

Where β_{total} represents the net total effect coefficient of digital marketing stimuli on consumer spend.

3.3.2 Bootstrapped Serial Mediation Regression System

To unbox the transmission mechanism (Hypotheses H2, H3, and H4), we specify a three-stage recursive panel equation system:

$$\begin{aligned} \text{Engagement}_{i,t} &= \alpha_1 + \beta_2 \text{DigitalMkt}_{i,t} + \sum_{k=1}^K \gamma_{1k} X_{k,i,t} + \mu_{1i} + \lambda_{1t} + \varepsilon_{1i,t} \\ \text{Trust}_{i,t} &= \alpha_2 + \beta_3 \text{DigitalMkt}_{i,t} + \theta_1 \text{Engagement}_{i,t} + \sum_{k=1}^K \gamma_{2k} X_{k,i,t} + \mu_{2i} + \lambda_{2t} + \varepsilon_{2i,t} \\ \ln Y_{i,t} &= \alpha_3 + \beta' \text{DigitalMkt}_{i,t} + \theta_2 \text{Engagement}_{i,t} + \theta_3 \text{Trust}_{i,t} + \sum_{k=1}^K \gamma_{3k} X_{k,i,t} + \mu_{3i} + \lambda_{3t} \\ &\quad + \varepsilon_{3i,t} \end{aligned}$$

Where β' is the direct effect coefficient, $\beta_2 \cdot \theta_2$ is the independent engagement mediation, $\beta_3 \cdot \theta_3$ is the independent trust mediation, and $\beta_2 \cdot \theta_1 \cdot \theta_3$ is the serial chain mediation effect. Standard errors and Bias-Corrected 95% Confidence Intervals (BC 95% CI) are calculated via 5,000 non-parametric Bootstrap resamples.

3.3.3 Multi-Group SEM and Group TWFE Panel Regressions

To capture latent variable measurement error and evaluate macroeconomic moderation across provincial per capita GDP tiers, a Maximum Likelihood Estimation (MLE) Structural Equation Model is formulated:

Structural Equation:

$$\eta_i = B\eta_i + \Gamma\xi_i + \zeta_i$$

Measurement Equations:

$$y_i = \Lambda_y \eta_i + \varepsilon_i, x_i = \Lambda_x \xi_i + \delta_i$$

To maintain complete methodological consistency, Multi-Group SEM is complemented by Group TWFE Panel Regressions (High-GDP vs. Low-GDP subsamples), evaluating parameter equality via Chi-Square difference tests ($\Delta\chi^2$).

4. Empirical Results and Discussion

4.1 Baseline Total Effect Model and Hypothesis H1 Verification

Table 2 reports the empirical estimation results for the baseline TWFE total effect model (Model 1) alongside the direct effect model containing mediators (Model 2).

In Model 1 (Baseline Total Effect Model), without introducing mediator variables, the coefficient of digital marketing stimulus is $\beta_{\text{total}} = 0.2479$ ($p < 0.001$, $t = 6.5241$). This confirms that digital marketing stimuli exert a highly significant positive total impact on Gen Z consumers' total spend. A 1 standard deviation increase in digital marketing exposure drives a 24.79% increase in monthly consumer spend, strongly supporting Hypothesis H1.

Table 2: Panel Regression Estimates: Total Effect vs. Direct Effect Models

Variable Category	Parameter Symbol	Model 1: Total Effect Model	Model 2: Direct Effect Model (With Mediators)
Digital Marketing Stimulus	DigitalMkt _{i,t}	0.2479* (0.0380)	0.1458* (0.0342)
Consumer Engagement (O_1)	Engagement _{i,t}	-	0.1245* (0.0281)
Trust Validation (O_2)	Trust _{i,t}	-	0.1582* (0.0315)
Consumer Age	Age _i	0.0158* (0.0062)	0.0124* (0.0052)
Consumer Gender (Female = 1)	Gender _i	0.0912*** (0.0245)	0.0842*** (0.0215)
Provincial Per Capita GDP	lnGDP _{i,t}	0.1620*** (0.0412)	0.1458*** (0.0382)
Provincial Population	lnPop _i	0.0715** (0.0268)	0.0631** (0.0241)
Individual Fixed Effects	μ_i	Included	Included
Month Fixed Effects	λ_t	Included	Included
Observations (N)	-	3,000	3,000
R-squared (R^2)	-	0.3812	0.4285
Model F -Statistic	-	38.45***	42.85***

Note: Standard errors clustered at the individual level are reported in parentheses. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$. Time-invariant demographic and regional characteristics (Age, Gender, Population) are benchmark reference estimates, while treatment effect results remain robust under individual fixed effects.

4.2 Serial Mediation Path Decomposition

Table 3 and Figure 1 present the 5,000-resample Bootstrap path decomposition results for the serial mediation system.

Table 3: Serial Mediation Path Decomposition and Bootstrap Confidence Intervals

Transmission Path Component	Mathematical Path Expression	Point Estimate	Boot Std. Err.	BC 95% CI Lower	BC 95% CI Upper	Relative Share (%)
Direct Effect	β'	0.1458***	0.0125	0.1210	0.1702	58.81%
Ind. Engagement Mediation	$\beta_2 \cdot \theta_2$	0.0524*	0.0068	0.0391	0.0662	21.14%
Ind. Trust Mediation	$\beta_3 \cdot \theta_3$	0.0312*	0.0042	0.0230	0.0398	12.59%
Serial Chain Mediation	$\beta_2 \cdot \theta_1 \cdot \theta_3$	0.0185*	0.0029	0.0128	0.0246	7.46%
Total Indirect Effect	Σ Indirect	0.1021***	0.0091	0.0825	0.1184	41.19%
Total Effect	β_{total}	0.2479***	0.0152	0.2150	0.2748	100.00%

The empirical results confirm all three mediation hypotheses:

- 1. **Independent Engagement Mediation (H2):** The indirect path through click frequency and cart additions yields a coefficient of **0.0524** (BC 95% CI [0.0391, 0.0662]), accounting for **21.14%** of the total effect, supporting **Hypothesis H2**.
- 2. **Independent Trust Mediation (H3):** The indirect path through time-varying product rating and fulfillment speed yields a coefficient of **0.0312** (BC 95% CI [0.0230, 0.0398]), accounting for **12.59%** of the total effect, supporting **Hypothesis H3**.
- 3. **Serial Chain Mediation (H4):** The sequential path "Digital Marketing Stimulus → Consumer Engagement → Trust Validation → Purchase Spend" yields a coefficient of **0.0185** (BC 95% CI [0.0128, 0.0246]), accounting for **7.46%** of the total effect, supporting **Hypothesis H4**.

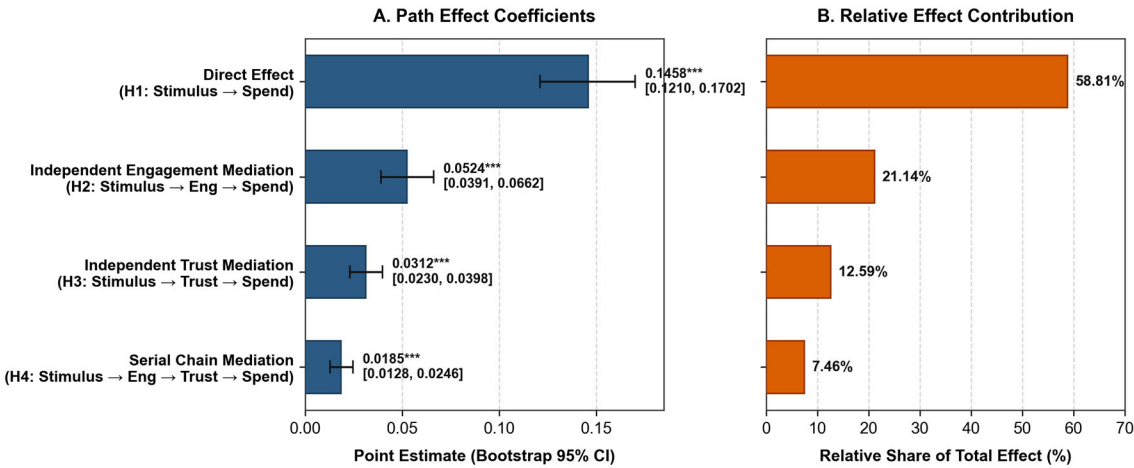


Figure 1: Path Effect Decomposition of Short-Form Video Marketing

4.3 Multi-Group SEM and Group TWFE Regional Economic Heterogeneity

To evaluate methodological consistency, Table 4 reports both Multi-Group SEM structural paths (with full fit metrics) and Group TWFE Panel Regressions across provincial per capita GDP tiers.

The overall SEM model demonstrates excellent goodness-of-fit across standard reporting metrics: $\chi^2/df = 1.84$, CFI = 0.968, TLI = 0.959, RMSEA = 0.038, and SRMR = 0.032, well within accepted academic thresholds.

Table 4: Multi-Group SEM and Group TWFE Estimates Across Regional GDP Tiers

Path / Parameter Component	High-GDP Provinces (N = 1,500)	Low-GDP Provinces (N = 1,500)	Group Coeff. Diff.	$\Delta\chi^2 / t\text{-Diff}$	p-Value
Multi-Group SEM: Trust → Spend (θ_3)	0.3842*	0.2215*	0.1627	14.85	0.0006
Multi-Group SEM: Serial Chain Effect	0.0215*	0.0142*	0.0073	11.20	0.0008
Group TWFE: Total Effect (β_{total})	0.2715***	0.2241***	0.0474	3.84*	0.0498
Group TWFE: Direct Effect (β')	0.1582***	0.1320***	0.0262	2.91	0.0880

The heterogeneity results show that regional economic development significantly moderates the trust gate ($\Delta\chi^2 = 14.85, p = 0.0006$). Gen Z consumers in economically developed provinces exhibit substantially higher sensitivity to fulfillment speed and product credibility when committing transaction spend.

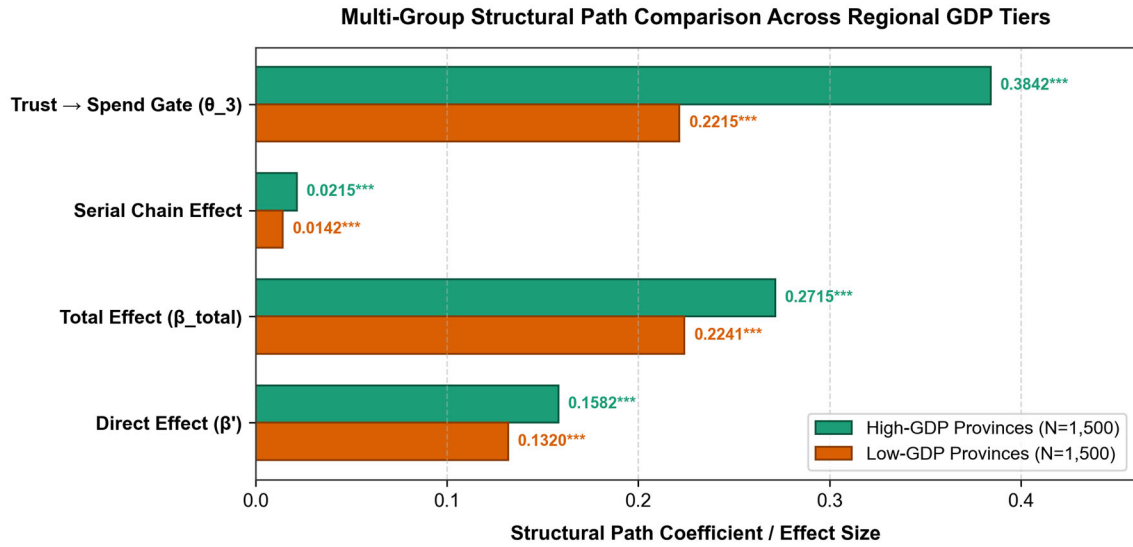


Figure 2: Multi-Group Structural Path Comparison Across Regional GDP Tiers

4.4 Robustness and Endogeneity Checks

To address potential selection bias and reverse causality in marketing exposure, three robustness checks were performed:

1. **One-Period Lagged Treatment Regression:** Replacing $DigitalMkt_{i,t}$ with its one-period lagged value ($DigitalMkt_{i,t-1}$) yields a robust positive total effect coefficient of $\beta_{total} = 0.1382$ ($p < 0.0001$), mitigating simultaneous feedback endogeneity.

2. **Alternative Dependent Variable Specification:** Substituting log total spend with log monthly order transaction count ($lnOrders_{i,t}$) yields consistent baseline positive results ($\beta_{total} = 0.1215, p < 0.001$).

3. **PSM-TWFE Estimation:** Applying Propensity Score Matching to pair high-exposure and low-exposure Gen Z users prior to TWFE estimation confirms a statistically significant Average Treatment Effect on the Treated (ATT) of 0.1350 ($p < 0.001$). Matching is performed using 1:1 nearest-neighbor matching based on consumer age, gender, and baseline period spend.

5. Main Conclusions, Strategic Implications, and Limitations

5.1 Empirical Conclusions

This study empirically unravels the influence mechanism of short-form video and digital marketing on Generation Z consumers' purchase behavior using a 6-month micro panel dataset ($N = 3,000$). First, baseline TWFE panel models establish a robust positive total effect of digital marketing stimuli on consumer spend ($\beta_{total} = 0.2479, p < 0.0001$), supporting H1. Second, bootstrapped mediation analyses confirm that marketing stimuli operate through a dual independent and serial chain transmission mechanism: stimulating digital engagement (O_1 , indirect effect 0.0524) and building trust validation (O_2 , indirect effect 0.0312), with the serial chain ("Digital Marketing Stimulus → Consumer Engagement → Trust Validation → Purchase Spend", indirect effect 0.0185) accounting for 7.46% of the total effect, supporting H2, H3, and H4. Third, multi-group SEM and group TWFE regressions demonstrate that regional economic development significantly moderates the trust gate ($\Delta\chi^2 = 14.85, p = 0.0006$), with higher-GDP consumers exhibiting greater trust sensitivity.

5.2 Strategic and Governance Implications

To address traffic conversion bottlenecks and trust vulnerability in digital commerce, three integrated strategic implications are highlighted: First, digital platforms and online merchants

must strengthen micro-level behavioral governance and information transparency by establishing verifiable disclosure systems for seller quality ratings and logistics delivery timelines, eliminating deceptive promotional claims and algorithmic misdirection to safeguard young consumers' trust; second, regulatory authorities and enterprise operators should optimize platform algorithmic risk management toolkits by implementing dynamic real-time recommendation recalibrations based on user feedback to prevent non-linear psychological resistance and filter-bubble fatigue; third, commercial stakeholders must foster differentiated market ecosystems tailored to regional economic heterogeneity, delivering premium fulfillment-guaranteed services in developed markets while emphasizing interactive engagement and value-for-money in emerging regions to construct a sustainable, multi-tiered digital commerce landscape.

5.3 Limitations and Future Research

This study has two main limitations: First, while the panel dataset controls for time-invariant individual heterogeneity over 6 months, future research should leverage quasi-natural experiments (e.g., platform algorithm updates) to further enhance causal identification. Second, the measurement of digital marketing stimuli focuses on aggregate exposure intensity; future studies could decompose content categories (e.g., live-streaming vs. user-generated short videos) to explore fine-grained psychological responses.

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Geographic Sciences

COP29: Qlobal İqlim böhranına qarşı mübarizədə yeni imkanlar və Azərbaycanın rolu

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Xülasə. Bu məqalə COP29-un qlobal iqlim siyasətindəki əhəmiyyətini və Azərbaycanın bu tədbirdə tutduğu rolu araşdırır. Sammit iqlim diplomatiyasının gücləndirilməsi, karbon emissiyalarının azaldılması, yaşıl enerji keçidinin sürətləndirilməsi, maliyyə mexanizmlərinin təkmilləşdirilməsi və ədalətli keçid prinsiplərinin tətbiqi baxımından əhəmiyyətli bir mərhələ kimi qiymətləndirilir. Sammitin əsas hədəfi ölkələrin öhdəliklərini gücləndirmək, iqlim maliyyələşməsini artırmaq, və Paris Sazişi çərçivəsində müəyyən olunmuş məqsədlərin həyata keçirilməsini təmin etməkdir. COP29 beynəlxalq miqyasda iqlim böhranı ilə mübarizədə yeni imkanlar açaraq, həm maliyyə, həm də siyasi baxımdan mühüm nəticələr ortaya qoymuşdur. Məqalədə sammitin gündəliyində duran əsas məsələlər-karbon emissiyalarının azaldılması, yaşıl enerji keçidi, maliyyə mexanizmləri, ədalətli keçid prinsipi, beynəlxalq əməkdaşlıq və Azərbaycanın ekoloji siyasəti geniş şəkildə təhlil edilmişdir.

Açar sözlər: COP29, iqlim siyasəti, yaşıl enerji, qlobal istiləşmə, Azərbaycan, Paris Sazişi

КС-29: Новые возможности и роль Азербайджана в борьбе глобальным климатическим кризисом

Резюме: В данной статье рассматривается значение КС-29 в глобальной климатической политике и роль Азербайджана в этом событии. Саммит считается важной вехой с точки зрения укрепления климатической дипломатии, сокращения выбросов углерода, ускорения перехода к зеленой энергетике, совершенствования финансовых механизмов и внедрения принципов справедливого перехода. Основная цель саммита — укрепить обязательства стран, увеличить финансирование мер по борьбе с изменением климата и обеспечить реализацию целей, изложенных в Парижском соглашении. КС-29 открыла новые возможности в борьбе с климатическим кризисом на международном уровне и принесла важные результаты как с финансовой, так и с политической точки зрения. В статье подробно анализируются основные вопросы повестки дня саммита: сокращение выбросов углерода, переход к зеленой энергетике, финансовые механизмы, принцип справедливого перехода, международное сотрудничество и экологическая политика Азербайджана.

Ключевые слова: КС-29, климатическая политика, зеленая энергетика, глобальное потепление, Азербайджан, Парижское соглашение

COP29: New Opportunities and Azerbaijan's Role in the Fight Against the Global Climate Crisis

Summary. *This article examines the importance of COP29 in global climate policy and the role of Azerbaijan in this event. The summit is considered an important milestone in terms of strengthening climate diplomacy, reducing carbon emissions, accelerating the green energy transition, improving financial mechanisms, and implementing the principles of a just transition. The main goal of the summit is to strengthen the commitments of countries, increase climate financing, and ensure the implementation of the goals set within the framework of the Paris Agreement. COP29 opened up new opportunities in the fight against the climate crisis on an international scale, and produced important results from both financial and political perspectives. The article extensively analyzes the main issues on the summit's agenda - reducing carbon emissions, green energy transition, financial mechanisms, the principle of a just transition, international cooperation, and Azerbaijan's environmental policy.*

Keywords: COP29, climate policy, green energy, global warming, Azerbaijan, Paris Agree

Giriş

XXI əsrdə global iqlim dəyişikliyi bəşəriyyətin qarşısında duran ən ciddi ekoloji və iqtisadi sınaqdır. Bu sınaqla mübarizədə beynəlxalq birliyin ən mühüm platforması olan BMT-nin İqlim Dəyişikliyi üzrə Çərçivə Konvensiyasının Tərəflər Konfransı (COP) hər il global yaşıl siyasətin istiqamətini müəyyən edir. Bakıda keçirilmiş COP29 sammiti Azərbaycanın müasir diplomatiya və iqtisadiyyat tarixində tamamilə yeni bir səhifə açmışdır. Bu tədbir Azərbaycanı ənənəvi qalıq yanacaq (neft-qaz) ixracatçısı olan bir ölkədən global yaşıl keçidin mərkəzi moderatoruna və yaşıl enerji mərkəzinə çevirdi. COP29 çərçivəsində əldə olunan tarixi razılaşmalar həm global miqyasda böhranların həllinə töhfə vermiş, həm də Azərbaycan üçün uzunmüddətli iqtisadi, ekoloji və geosiyasi imkanlar pəncərəs açmışdır. Bakıda keçirilən COP29 konfransı global miqyasda, dövlətlər və özəl sektor üçün trilyon dollarlıq yeni iqlim maliyyəsi bazarlarına rəsmi **çixış** və beynəlxalq investisiya imkanları yaratmışdır. Bu platforma iqlim fəaliyyətini sadəcə ekoloji öhdəlikdən çıxararaq onu böyük bir iqtisadi fürsətə çevirmişdir.

Məsələnin qoyuluşu və tədqiqatın nəticələri

Azərbaycanın paytaxtı Bakı şəhərində keçirilən COP29 konfransı, global iqlim böhranı ilə mübarizədə bəşəriyyətin gələcək onilliklərdəki iqtisadi və ekoloji xəritəsini müəyyən edən ən kritik dönüş nöqtələrindən biri olmuşdur. İqlim dəyişikliyinə fəsadlarının, xüsusilə anomal istilərin, su qıtlığının və ardıcıl təbiət fəlakətlərinin global miqyasda pik həddə çatdığı bir dövrdə təşkil edilən bu sammit, illərdə beynəlxalq danışıqlarda davam edən durğunluğu sındırmağı bacarmışdır. Paris Sazişinin hədəflərini sadəcə kağız üzərindəki bəyanatlardan real icra müstəvisinə keçirmək məqsədi daşıyan bu konfrans, iqlim mübarizəsinin qarşısında dayanan ən böyük maneələri, yəni maliyyə çatışmazlığını və hüquqi boşluqları birbaşa hədəf alaraq həll yolları təklif etmişdir. Beynəlxalq birlik tərəfindən "Maliyyə COP-u" kimi xarakterizə edilən bu tədbir, iqlim böhranı ilə mübarizəni sadəcə bir ekoloji öhdəlik olmaqdan çıxararaq, onu global iqtisadiyyatın yeni inkişaf modelinə çevirmişdir.

Bu tarixi konfransın iqlim böhranının həllinə verdiyi ən mühüm töhfə, Yeni Kollektiv Kəmiyyət Hədəfi çərçivəsində qəbul edilən "Bakı Maliyyə Məqsədi" adlı yeni global iqlim maliyyəsi memarlığının qurulmasıdır. İllərdə inkişaf etməkdə olan yoxsul ölkələrin yaşıl keçidi üçün ayrılması

nəzərdə tutulan, lakin icrasında daim gecikmələr yaranan illik 100 milyard dollarlıq köhnə hədəf Bakıda kökündən dəyişdirilmişdir. Əldə olunmuş tarixi razılaşmaya əsasən, inkişaf etmiş zəngin dövlətlərin birbaşa dövlət mənbələrindən ayıracağı illik əsas maliyyə öhdəliyi üç dəfə artırılaraq 300 milyard dollara çatdırılmışdır. Bununla belə, COP29-un əsl miqyası qlobal bazarların, özəl investisiya fondlarının və çoxtərəfli inkişaf banklarının da bu prosesə cəlb edilməsi ilə 2035-ci ilə qədər hər il minimum 1.3 trilyon dollar vəsaitin iqlim fəaliyyətinə səfərbər edilməsi hədəfinin qoyulması ilə ölçülür. Bu nəhəng maliyyə paketi, iqlim dəyişikliyindən ən çox əziyyət çəkən zəif iqtisadiyyatlı ölkələrin kömür və digər qalıq yanacaqlardan uzaqlaşaraq bərpa olunan enerji mənbələrinə sürətli keçidini maliyyələşdirmək üçün misilsiz bir imkan yaradır.

Maliyyə hədəfləri ilə yanaşı, COP29 çərçivəsində təxminən on ildir ki, beynəlxalq diplomatik danışıqlarda dalana dirənən Paris Sazişinin 6-cı maddəsinin, xüsusilə də 6.4-cü bəndinin tam həcmdə qəbul edilməsi iqlim böhranı ilə mübarizədə inqilabi bir addım olmuşdur. Bu qərarla Birləşmiş Millətlər Təşkilatının rəsmi nəzarəti altında fəaliyyət göstərəcək vahid, şəffaf və mərkəzləşdirilmiş qlobal karbon ticarəti bazarı rəsmən işə salınmışdır. Yeni mexanizm imkan verir ki, meşə salan, ekoloji texnologiyalar tətbiq edən və ya karbon emissiyalarını azaldan ölkələr ilə şirkətlər bu fəaliyyətlərini rəsmi karbon kreditinə çevirərək yüksək emissiyaya malik zəngin dövlətlərə sata bilsinlər. Bu rəsmi bazarın işlək vəziyyətə gətirilməsi milli iqlim planlarının icra xərclərini qlobal miqyasda illik 250 milyard dollar azaldacaq və müəssisələrin ekoloji layihələri imitasiya etdiyi "yaşıl yuyulma" fırıldaqlarının qarşısını tamamilə alacaqdır.

Bakı konfransının iqlim ədalətinin təmin olunmasındakı digər böyük uğuru isə qlobal emissiyalarda demək olar ki, heç bir payı olmayan, lakin fəlakətlərdən ən çox zərər çəkən kiçik ada dövlətlərini qorumaq üçün İtki və Zərər Fondunun tam fəaliyyətə gətirilməsidir. Ötən konfranslarda əsası qoyulsa da, hüquqi və bürokratik mexanizmləri müəyyən edilməmiş bu fond, COP29-da qəbul edilən qərarlarla rəsmən bank əməliyyatlarına və vəsaitlərin paylanmasına hazır status almışdır. Bunun sayəsində tayfunlar, dəniz səviyyəsinin qalxması və ya quraqlıq səbəbindən dağıntılara məruz qalan yoxsul icmalar artıq uzunmüddətli bürokratik əngəllərlə qarşılaşmadan birbaşa və sürətli kompensasiya ala biləcəklər. Eyni zamanda, sammit çərçivəsində qəbul edilən "Bakı Harmoniya İqlim Təşəbbüsü" kənd təsərrüfatı sektorunu və kiçik fermerləri dəstəkləyərək qlobal ərzaq təhlükəsizliyini iqlim böhranının təsirlərindən qorumaq üçün fərqli fondlar arasında güclü koordinasiya yaratmışdır. Karbon qazından daha sürətli isinməyə səbəb olan metan emissiyalarının azaldılmasına dair üzvi tullantılar üzrə qlobal bəyannamənin qəbulu isə şəhərlərin ekoloji idarəetməsində yeni səhifə açmışdır.

Yekun olaraq qeyd etmək lazımdır ki, COP29 konfransı qlobal temperatur artımını sənayeləşmədən əvvəlki dövrlə müqayisədə kritik 1.5°C səviyyəsində saxlamaq barədə verilən bəşəri sözün hələ də qüvvədə olduğunu sübut etdi. Bakı danışıqları dünya liderlərinə, transmilli korporasiyalara və beynəlxalq təşkilatlara göstərdi ki, iqlim dəyişikliyi ilə mübarizə sadəcə humanitar yardım və ya xeyriyyəçilik deyil, yeni eranın ən böyük iqtisadi və texnoloji hərəkətverici qüvvəsidir. Bu platformada əldə olunan tarixi konsensus, bəşəriyyəti sadəcə problem barədə danışmaq mərhələsindən çıxararaq trilyon dollarlıq investisiyaların və sərt qanunların tətbiq olunduğu real icraat mərhələsinə daşımışdır.

COP29-un İqlim böhranına qarşı mübarizədə yaratdığı imkanlar:

Özəl Sektor və Biznes üçün İmkanlar

- Yeni Karbon Bazarı: Paris Sazişinin 6.4-cü maddəsinin tam qəbulu ilə şirkətlər qlobal standartlara uyğun rəsmi karbon kreditləri alıb sata bilirlər.
- Yaşıl İnvestisiya Axını: Şirkətlər ekoloji layihələr, bərpa olunan enerji və enerji səmərəliliyi üçün beynəlxalq fondlardan daha asan maliyyə cəlb edə bilirlər.

- ESG Uyğunluğu: Bizneslərin global tədarük zəncirinə integrasiyası və beynəlxalq tərəfdaşlıqlar qurması üçün hüquqi zəmin güclənmişdir.

İnkişaf Etməkdə Olan Ölkələr üçün Maliyyə İmkanları

- 300 Milyard Dollarlıq Birbaşa Fond: İqlim dəyişikliyinə fəsadları ilə mübarizə və yaşıl keçid üçün birbaşa qrant və güzəştli kredit imkanları 3 dəfə artmışdır.
- İtki və Zərər Fondu: İqlim fəlakətlərindən zərər çəkən ölkələr və kiçik ada dövlətləri üçün birbaşa və sürətli kompensasiya mexanizmi işə düşmüşdür.

2.1. Azərbaycanın COP29-dəki Rolu:

- "Bakı Maliyyə Məqsədi" (Baku Finance Goal): Sammitin ən böyük tarixi nailiyyəti Azərbaycanın rəhbərliyi ilə inkişaf etməkdə olan ölkələrin iqlim fəaliyyətini dəstəkləmək üçün hər il **1,3 trilyon dollar** (bunun 300 milyard dolları birbaşa inkişaf etmiş ölkələr tərəfindən idarə olunmaqla) həcmində maliyyə hədəfinin qəbul edilməsi oldu. Bakı bu razılaşma ilə global maliyyə arxitekturasının formalaşdığı mərkəz kimi tarixə düşdü.
- Paris Sazişinin 6-cı Maddəsi: Beynəlxalq karbon bazarlarının tam fəaliyyətə başlaması üçün təxminən 10 ildir uzanan müzakirələr məhz Bakıda yekunlaşdı və qaydalar təsdiq olundu.
- Körpü Rolu: Azərbaycan sammit ərzində Qlobal Cənub (inkişaf etməkdə olan ölkələr) ilə Qlobal Şimal (inkişaf etmiş zəngin ölkələr) arasında kompromis yaradan diplomatik körpü missiyasını uğurla icra etdi.
- Birbaşa Yardım: İqlim fəsadlarından ən çox əziyyət çəkən yoxsul və ada dövlətləri üçün nəzərdə tutulan İtki və Zərər Fondu tam fəaliyyətə gətirildi və vəsaitlərin paylanmasına hazır vəziyyətə gətirildi.

2.2. COP29-un Azərbaycan Üçün Yaratdığı İqtisadi və İnvestisiya İmkanları

- Yaşıl Enerji Potensialının Təqdimatı: Azərbaycan özünün nəhəng bərpa olunan enerji potensialını (quruda 135 QVt, Xəzər dənizində isə 157 QVt külək enerjisi) dünya investorlarına nümayiş etdirdi. BƏƏ-nin "Masdar", Səudiyyə Ərəbistanının "ACWA Power" və digər beynəlxalq şirkətlərlə yeni meqa-layihələrin təməli qoyuldu.
- Xidmət və Turizm Sektorunun **Sıçrayışı**: Sammit dövründə xarici turist axınında 148%, POS-terminal xərclərində isə 236% artım qeydə alındı. Bu, daxili xidmət, hotelçilik və nəqliyyat sektoruna qısa müddətdə milyonlarla dollar birbaşa vəsait daxil olması deməkdir.
- İnfrastruktur və Rəqəmsallaşma: Bakı və ətraf ərazilərdə nəqliyyat sistemi, rəqəmsal idarəetmə və "ağıllı şəhər" elementləri beynəlxalq standartlara uyğunlaşdırıldı.

2.3. Regional Ekologiya və Azad Edilmiş Ərazilərin "Yaşıl Zona" Konsepti

- Qarabağ və Şərqi Zəngəzur: İşğaldan azad edilmiş ərazilərin **"Net-Sıfır Emissiya"** və **"Yaşıl Enerji"** zonasına çevrilməsi strategiyası beynəlxalq müstəvidə rəğbətlə qarşılandı və xarici ekoloji fondların bu bölgəyə diqqəti artdı.
- Qlobal Təşəbbüslər: Azərbaycan tərəfindən irəli sürülən "Bakı Su Dialoqu" kimi regional təşəbbüslər Xəzər dənizinin və regionun su ehtiyatlarının qorunmasında ölkəmizin liderliyini möhkəmləndirdi.

2.4 Bakı Təşəbbüsləri və Qlobal Bəyannamələr

- Bakı Harmoniya İqlim Təşəbbüsü: Fermerlərin iqlim dəyişikliyinə uyğunlaşması və kənd təsərrüfatının davamlılığının artırılması hədəfləndi.
- Metan Qazının Azaldılması: Üzvi tullantılardan yaranan metan qazının azaldılması üzrə qlobal bəyannamə qəbul edildi.
- Multisektoral Sahələr: Şəhərlər, turizm sektoru və səhiyyə sistemlərinin "yaşıl keçid" layihələrinə uyğunlaşdırılması üçün mühüm sənədlər imzalandı.

Nəticə

Nəticə olaraq, COP29 konfransı qlobal temperatur artımını sənayeləşmədən əvvəlki dövrlə müqayisədə kritik 1.5°C səviyyəsində saxlamaq barədə verilən bəşəri sözün hələ də qüvvədə olduğunu sübut etdi. Bakı danışıqları dünya liderlərinə, transmilli korporasiyalara və beynəlxalq təşkilatlara göstərdi ki, iqlim dəyişikliyi ilə mübarizə sadəcə humanitar yardım və ya xeyriyyəçilik deyil, yeni eranın ən böyük iqtisadi və texnoloji hərəkətverici qüvvəsidir. Bu platformada əldə olunan tarixi konsensus, bəşəriyyəti sadəcə problem barədə danışmaq mərhələsindən çıxararaq trilyon dollarlıq investisiyaların və sərt qanunların tətbiq olunduğu real icraat mərhələsinə daşımışdır.

COP29 sammiti Azərbaycanın beynəlxalq arenadakı çəkisini və nüfuzunu keyfiyyətcə yeni bir mərhələyə qaldırdı. Ölkəmiz bu tədbirdə sadəcə qonaqpərvər bir ev sahibi deyil, həm də qlobal böhranların həllində prinsipial, strateji və nəticəyönümlü qərarlar qəbul etdirən lider dövlət rolunda çıxış etdi. Sammitin Azərbaycan üçün yaratdığı imkanlar müvəqqəti xarakter daşımır; əksinə, cəlb olunan milyardlarla dollarlıq yaşıl investisiyalar, qlobal karbon bazarına integrasiya və turizm infrastrukturunun inkişafı ölkənin gələcək onilliklərdəki dayanıqlı inkişaf xəttini müəyyən edir. Yekun olaraq qeyd etmək lazımdır ki, COP29 Azərbaycanın neft-qaz dövründən "yaşıl və rəqəmsal iqtisadiyyat" dövrünə keçidini uğurla rəsmiləşdirən tarixi bir zirvə nöqtəsi oldu.

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5. Ekologiya və Təbii sərvətlər Nazirliyinin Xəbəri: COP29-un Azərbaycanda keçiriləcəyi, 2030 və 2050 hədəfləri və konfransın əhəmiyyəti haqda məlumatlar.
6. Media işıqlandırması mövzusu (*media.gov.az*) COP29 ilə bağlı Azərbaycanda təqdim olunan medianın həcmi-60 000-ə yaxın link, media orqanlarının rolu, sosial şəbəkə reaksiyaları və s.
7. Modern.az yazısı: "Azərbaycan mediasının COP29 sınağı" adlı məqalə.
8. Azərbaycan dilində Vikipediya- "BMT-nin İqlim Dəyişmələri Konfransı (2024)" (Bakı).

Methodological aspects of river basin management and the integrated assessment of water resources in the context of Kazakhstan's environmental security

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Abstract. This article presents a systematic study of environmental security issues in the Republic of Kazakhstan in the context of effective water resource management. The methodological basis of the study is a comprehensive analysis of transboundary risks and water scarcity, conducted using verified statistical data and the latest findings from state monitoring programmes. The authors analyse the quantitative and qualitative characteristics of surface and groundwater in the country's eight river basins, paying particular attention to the critical dependence of the national water balance on transboundary inflows, which account for 46 per cent of total available resources.

The study identified and classified the key determinants of the region's water vulnerability: natural spatial and temporal unevenness in runoff distribution, a high degree of infrastructure deterioration (resulting in losses of up to 60 per cent during transmission) and progressive anthropogenic pollution of water bodies, reaching quality classes 4 and 5. The article examines in detail the evolution of the regulatory framework and the effectiveness of government strategies (the 'Drinking Water', 'Ak Bulak', 'Nurly Zhol' and 'Strategy to 2030' programmes) in the field of modernising the water sector.

Keywords: Water security, comprehensive risk analysis, transboundary watercourses, river basin management, water scarcity, state monitoring

Introduction

The availability and quality of water resources are fundamental to the sustainable socio-economic development of the Republic of Kazakhstan. The country's geographical location results in naturally limited and extremely unevenly distributed water resources. Against the backdrop of global climate change and growing anthropogenic pressure, the issue of ensuring water security has become a strategic challenge for the national ecosystem and public health.

This study is based on a comprehensive analysis of transboundary risks and water scarcity, conducted through an in-depth examination of statistical data and the results of state monitoring programmes.

The aim of this study is to provide a scientific basis for the transition to a rational system of river basin management and the introduction of innovative tools, such as the 'Smart Water' project and the best available technologies. The incorporation of comprehensive monitoring data into scientific discourse enables not only an assessment of the current vulnerability of Kazakhstan's eight river basins, but also a forecast of water scarcity risks up to 2040, whilst proposing avenues for improving national water policy.

Literature review

One of the most important factors determining a country's sustainable socio-economic development is the availability and quality of its water resources. The geographical characteristics of the Republic of Kazakhstan result in limited water resources, as well as the natural territorial and seasonal unevenness in the distribution of water resources, which in turn leads to water shortages in certain regions and, consequently, to a deterioration in the ecological state of the natural environment, the drying up and pollution of lakes and rivers, and an increase in the incidence of disease amongst the population. Within the country, the central region accounts for 2.6 per cent of all water resources, the northern region for 4.2 per cent, the western region for 13.4 per cent, the south-eastern region for 24.1 per cent, the southern region for 24.1 per cent, and the eastern region for 34.5 per cent.

Kazakhstan has around 39,000 rivers and seasonal watercourses. Glaciers are the main source feeding the rivers. Most rivers belong to the inland closed basins of the Caspian and Aral Seas, and the lakes Balkhash, Alakol and Teniz. The Irtysh River belongs to the Arctic Ocean basin. The country has more than 7,000 rivers with a channel length of over 10 km. These major rivers include: the Ural, Irtysh, Syr Darya, Esil, Ili, Tobyl, Sagiz, the Greater and Lesser Uzen, Torgay, Irgiz, Nura, Selety, Sarysu, Black Irtysh, Arys, Talas, Shu, Karatal, Aksu, Lepsy and others.

There are over 48,000 lakes (measuring 1 hectare or more) in Kazakhstan, with a total area of around 45,000 km². In terms of number, small lakes (less than 1 km²) account for 94 per cent, whilst in terms of area, they account for 10 per cent. There are around 3,000 large lakes (over 1 km²), whilst there are only 22 lakes with an area exceeding 100 km². All lakes share the following general characteristics: they are closed basins, shallow, and experience sharp fluctuations in water levels and volumes throughout the year. The largest lakes in Kazakhstan are the republic's sections of the Caspian and Aral Seas, Lakes Balkhash and Tengiz in Central Kazakhstan, Alakol and Sasykkol near the Dzungarian Gate, and Zaisan and Markakol in Eastern Kazakhstan. A large number of lakes are situated in the forest-steppe and northern parts of the steppe zone. The largest of these are Korgalzhyn, Chelkar-Tengiz, Bolshoye Chebachye, Shchuchye and Selety-Tengiz (Fizicheskaya geografiya Respubliki Kazakhstan, 2010).

The total volume of water in the country's lakes is 190 km³, of which about 20 km³ is fresh water. The republic also has more than 4,000 reservoirs and dams, with a total area of 10,000 km² and a water volume of about 90 km³. These serve as sources of water and electricity for industrial centres, and are also suitable for irrigating agricultural land. The largest of these are: Bukhtarma, Kapshagayagay, Shardara, Bogen, Temirtau and Sergeyev. Medium-sized reservoirs include: Akkol,

Teris-Ashchybulak, Zhemsau, Kamyskol, Ural, Taiketken, Zhelkuar, Karatamar, Sherbainur, Kengir, Saryshyganak, Kurtin, Teles, Shunkyr and others.

The available water resources of the river flow of all rivers in Kazakhstan, given the current level of surface water research, are estimated at 100 km³/year, of which 54 km³ originate within the republic and 46 km³ in neighbouring countries (China – 21.2 km³, Uzbekistan – 14.6 km³, the Kyrgyz Republic – 3.1 km³, and Russia – 7.5 km³). The volume of proven groundwater reserves amounts to approximately 15 km³/year and is replenished by such renewable natural resources as atmospheric precipitation, river flow, and others. The main groundwater reserves are located in the Balkhash-Alakol and Irtysh basins (66 per cent of total reserves). Within the territory of the Republic of Kazakhstan, the State Register has identified 4,324 groundwater deposits (5,282 sites) with approved exploitable reserves totalling 43,076.865 thousand m³/day.

Large reserves of fresh water are concentrated in glacial masses. In Kazakhstan, there are 927 moraine-glacial and glacial-dammed lakes, of which 675 are located in the Almaty Region, 146 in the East Kazakhstan Region, 42 in the Turkestan Region, 37 in the city of Almaty, 27 in the Zhambyl Region; their number is increasing year on year.

Across the country as a whole, over the past five years, annual water consumption across all sectors of the economy has averaged 24 km³, with 85 per cent coming from surface water. Across the republic's individual regions, the situation regarding the availability of surface and groundwater resources varies significantly. The Irtysh River basin and the Balkhash–Alakol basin are the best supplied with both surface and groundwater resources. The Nura-Sarysu, Esil, Tobyl - Torgay basins are experiencing a shortage of groundwater. Significant areas of the Esil, Ural-Caspian, Aral-Syr Darya, Tobyl -Torgay and Nura-Sarysu basins are already experiencing a shortage of both surface and groundwater.

An essential component of national water policy is the effective management of water resources, and the transition to the sustainable use of water resources requires the establishment of a rational management system. Kazakhstan was one of the first countries in the post-Soviet space to introduce a management approach based on river basin districts.

Eight river basin districts have been identified within the republic: the Aral-Syr Darya, the Balkhash-Alakol (Ministry of Ecology, Geology and Natural Resources [MEGNR], 2021).

Each of these river basins faces regional environmental challenges relating to water use and the quality of surface water.

The Aral–Syr Darya Water Management Basin. The basin covers an area of 345,000 km³. The main watercourse of the basin is the lower reaches of the Syr Darya River. Around 90 per cent of the river flow in the Aral-Syr Darya river basin originates from neighbouring countries. The length of the river within Kazakhstan, from the Shardara Reservoir to the Aral Sea, is 1,627 km. The largest tributaries of the Syr Darya River within Kazakhstan are the Keles, Arys, Badam, Borolday and Bugun rivers, as well as smaller rivers flowing from the slopes of the Karatau Range (UNECE, 2019).

In 1960, signs of a disruption to the ecosystem's homeostasis were detected in the Aral–Syr Darya basin. In earlier times, the uncontrolled use of water resources from the Syr Darya and Amu Darya rivers for agricultural purposes led to a reduction in the volume of river flows entering the Aral Sea. For example, whilst between 1910 and 1960 an average of around 62 cubic kilometres of water reached the Aral Sea each year, this figure fell to 16.7 cubic kilometres between 1971 and 1980, and to 3.5 cubic kilometres between 1981 and 1990. Between 1974 and 1986, the Syr Darya's flow did not reach the Aral Sea. Over the 42-year period from 1960 to 2002, the level of the Aral Sea fell by more than 22 metres. The average rate of decline was over 0.5 metres per year. The sea's surface area has shrunk by almost 3.5 times, and its volume by more than 8 times. In 1989, the Aral Sea split into two parts – the Great Aral Sea and the Small Aral Sea. Whereas the Syr Darya River previously flowed into the Aral Sea, it now flows into the northern part of the sea – the Small Aral Sea.

At present, the problem facing the basin is that water resources do not meet the needs of the population and economic sectors, which is hindering the region's further socio-economic development. Water abstraction for agricultural purposes accounts for 98 per cent of the total in this river basin, as it is home to over 60 per cent of the country's irrigated land (in the Turkestan and Kyzylorda regions), where the most water-intensive crops, such as rice and cotton, are grown. In addition to irrational water use and transboundary issues, there are critical challenges related to deteriorating water management infrastructure and increasing anthropogenic pollution, which further aggravate the regional water deficit.

The Balkhash-Alakol Water Management Basin. The Balkhash-Alakol Basin covers a vast area in south-eastern Kazakhstan and part of the neighbouring territory of China. The main water body in the Balkhash-Alakol Basin is the Ili River, the flow of which is regulated by the Kapshagayagay Reservoir. The basin is divided into two natural water bodies: the Lake Balkhash basin and the Lake Alakol basin. The Ili River basin accounts for 80 per cent of the total surface runoff into Lake Balkhash, 70 per cent of which is located in China, where the rapid expansion of agriculture threatens to cause an even greater reduction in the water supply to Lake Balkhash. The water resources in this basin are substantial, totalling 149.4 km³, but the bulk of the water (77 per cent) is contained in lakes, primarily Lake Balkhash. It should be noted that between 1941 and 2020, there were periods of both falling and rising lake levels. The amplitude of these water level fluctuations was approximately 3 m. The lowest water level in the lake was recorded in 1987 following the completion of the filling of the Kapshagayagay Reservoir, whilst in January 2005 the level rose to 342.5 metres, due to the high amount of rainfall during those years. At present, measures need to be taken to maintain the water level of Lake Balkhash at 342 metres according to the Baltic Height System.

Changes to the hydrological regime of the Kapshagay Reservoir have led to the degradation of the Ili River delta; its area has decreased by a factor of 1.6 – that is, whilst in 1970 its area was 3,046 km², it has now shrunk to 1,876 km². As a result, the water supply to the lake systems has decreased. Of the 16 lake systems, only 5 remain. In these, water salinity has increased, as have the levels of pesticides and heavy metals, both in the water and in the bottom sediments, as well as in phytoplankton, zooplankton and fish tissues (UNDP, 2010).

In the Balkhash-Alakol water management basin, 83 per cent of the total water abstracted is used in agriculture, where losses amount to 1.0 km³ of the total water abstracted. Lake Balkhash is polluted by anthropogenic sources of zinc, nickel, manganese and persistent organic pollutants. Bertis Bay and Torangalyk Bay are most affected by anthropogenic impacts from the 'Balkhashtsvetmet' enterprise, resulting in increased concentrations of heavy metals (*Kontseptsiya razvitiya sistemy upravleniya vodnymi resursami...*, 2021).

At present, the main issues in bilateral relations between the Republic of Kazakhstan and the People's Republic of China regarding the joint use of water resources concern the proposed increase in water abstraction within the territory of the PRC from the transboundary rivers Ili and Irtysh (from 0.5–1 to 2–4 km³/year). This entails a number of negative consequences for Kazakhstan, both socio-economic (disruption to a number of industrial enterprises, damage to the fishing and agricultural sectors, and water pollution from industrial waste) and environmental (climatic aridisation, disruption to the natural water balance and ecological equilibrium) (EU-UNDP, 2010).

In the Balkhash-Alakol Basin, there is a need for intergovernmental cooperation between Kazakhstan and China, an inter-basin strategy for the joint use of resources, and a cross-sectoral allocation between the lake and irrigated agriculture, whereby it is envisaged that the basin level can be maintained at 341 metres.

The Irtysh Water Management Basin. The Irtysh river basin comprises the River Irtysh and its tributaries; it is one of the largest rivers in Kazakhstan. Its total length, including the Black Irtysh,

is 4,200 km. There are three major reservoirs on the Irtysh River within Kazakhstan: Bukhtarma, Ust-Kamenogorsk and Shulba, which help to regulate the river's flow. This is the transboundary basin with the most abundant water resources. The water resources total 43.8 km³. The main water reserves are formed by river flow, amounting to 26.04 km³ (59 per cent). The volume of the reservoirs is 7.7 km³, the largest in Kazakhstan. The lakes contain approximately the same amount of water – 16 per cent.

The water balance in the Irtysh basin is under strain, as the Irtysh River currently serves as a source for industrial and domestic/drinking water purposes. Consequently, the top priority is to improve the water quality of the Irtysh River (Class 4). Mining and metallurgical enterprises in Eastern Kazakhstan are the main sources of pollution in the Irtysh River with metals – iron, copper, zinc and cadmium – as well as ammonium ions and sulphates.

Due to the operation of the Bukhtarma and Shulba reservoirs for hydroelectric power generation, there are issues with flooding of the Irtysh river floodplain during the spring flood season. Furthermore, the People's Republic of China's decision to utilise part of the Irtysh river's flow may have a negative impact on Kazakhstan's environment and economy.

The Esil River Basin. The Esil River Basin covers an area of 245,000 km² in Kazakhstan. Most of the water resources are concentrated in lakes (55 per cent) and river flow (34 per cent), whilst 7 per cent is stored in reservoirs. The main watercourse is the Esil River.

This basin is subject to high pressure on local water resources, as 96 per cent of them are used for domestic and industrial purposes. Water losses in the water supply systems amount to 15–20 per cent, which is due to worn-out, ageing water supply networks. Specific measures must be taken to establish a reserve water source for the city of Astana's drinking water supply.

According to the unified water quality classification system, the Esil River is classified as Class 4, with the main pollutants being phenols, suspended solids and magnesium.

The Ural-Caspian Water Management Basin. The main watercourses of the basin are the Ural (Zhayik), Emba, Sagiz and Uil rivers. The basin's long-term water resources amount to 16.0 km³, of which 10.5 km³ are formed within the territory of the Russian Federation. Within Kazakhstan, the Ural-Caspian water management basin covers an area of 415,000 km² and includes the catchment area of the Ural River (236,000 km²), the Volga-Ural inter-river basin (107,000 km²) and the Ural-Emba inter-river basin (72,000 km²). The water resources total 28.0 km³, comprising 11.4 km³ in the Ural River basin, 13.4 km³ in the Volga River basin and 1.5 km³ in the basins of the Uil, Sagiz and Emba rivers. River water accounts for 97 per cent, whilst groundwater accounts for 3 per cent (United Nations, 2019).

Even in Soviet times, great importance was attached to the protection of the River Ural, part of which had protected status. In 1972, the Government of the USSR adopted a resolution 'On measures to prevent the pollution of the Volga and Ural river basins by untreated waste water'. In 1977, on the initiative of the Central Committee of the Communist Party of the Soviet Union and the All-Russian Society for Nature Conservation, a proposal was put forward to establish a permanent inter-republican public committee for the protection, rational use and restoration of the natural resources of the Ural River basin. Following the collapse of the USSR, issues concerning the River Ural came to be governed by agreements between the Governments of the Russian Federation and the Republic of Kazakhstan on the joint use and protection of transboundary water bodies, dating from 1992, 2010, 2016, and by the Russian-Kazakh Commission on the Joint Use and Protection of Transboundary Water Bodies in the Ural River Basin.

In 2018, the water level in the Ural reached a record low. Despite cooperation with the Russian Federation and measures to preserve the Ural River, a continuing trend towards shallowing is observed, which poses a threat to Kazakhstan's water security.

71 per cent of the river's flow originates in the Russian Federation. Due to the river's regulation and the discharge of pollutants from the Russian Federation, the main problem facing

the basin is the shallowing and pollution of the River Ural. Under the unified water quality classification system, the River Ural is classified as Class 4. Heavy metals – including copper, zinc, lead, cobalt, nickel, chromium and iron – are among the most dangerous pollutants affecting the Ural River. The Yelek River, which is heavily polluted with heavy metals (chromium, copper, fluorides and boron compounds), contributes significantly to the pollution of the Ural River. Due to natural and climatic factors, there has been a decline in the flow of the Oil, Zhem, Saryozen and Karaozen rivers in recent years, which is having a negative impact on the environmental situation in the Atyrau and West Kazakhstan regions and is acting as a constraint on economic development.

The Nura-Sarysu Water Management Basin. The main rivers in the basin are the Nura and the Sarysu. There are around 2,000 lakes and more than 400 artificial reservoirs within the basin. The water resources total 4.59 km³ (Satenbayev et al., 2012).

A distinctive feature of this region is that the river basin is an area of insufficient moisture. Moreover, the bulk of the annual flow (up to 90 per cent or more) occurs during the short spring flood period, whilst during the summer, autumn and winter low-water periods, river discharge decreases significantly, and on most rivers there is no flow at all during this time.

In the second half of the 20th century, the 'Carbide' chemical plant discharged around 1,000 tonnes of mercury into the Nura River, causing significant damage to the environment and living organisms. The mercury is in a sorbed state and therefore does not pose a serious threat to the life and health of the local population.

Since 2001, a comprehensive programme of large-scale measures has been implemented to remediate mercury pollution in the river. The project was funded by the Government of Kazakhstan and the World Bank.

The Nura-Sarysu basin is subject to high pressure on its water resources, 88 per cent of which are used for industrial purposes and are fully incorporated into the economic cycle. Furthermore, there is a problem regarding the water quality of the basin's main rivers. For example, according to the 'Unified Classification of Water Quality in Water Bodies', the Nura River is classified as Class 4, whilst the Kara-Kengir River is classified as Class 5, which confirms the need to adopt environmental protection measures to prevent the discharge into these rivers of key pollutants such as magnesium, total phosphorus, ammonium, etc., from entering them.

The Tobyl -Torgay Water Management Basin. The main watercourses of the basin are the Tobyl, Torgay and Irgiz rivers, which together cover an area of 214,000 km². The flow regime of the basin's rivers is primarily regulated by the Verkhnetobolsk and Karatamar reservoirs. This is the basin with the poorest water resources.

The 'historical pollution' of the Tobyl River is linked to the fact that the river's floodplain contains a storage site for industrial effluents from a former copper-ammonia production facility, which ceased operations in the 1980s. Environmental monitoring results periodically indicate a negative impact of this waste deposit on the river's water quality.

The water resources total 2.9 km³. Groundwater accounts for 15 per cent; the remainder comes from surface sources: 33 per cent in lakes, 17 per cent in reservoirs and 35 per cent in rivers.

This basin experiences low pressure on water resources. The available river flow resources of the Tobyl-Torgay basin amount to 2.1 km³, of which 29 per cent of the flow originates within the territory of the Russian Federation. Water losses in the region's water supply systems amount to 20 per cent, necessitating measures to reduce them. According to the 'Unified Classification of Water Quality in Water Bodies', the water quality of the Tobyl River falls into the worst category, Class 5. The causes of the poor water quality include discharges from industrial enterprises, domestic and commercial wastewater, runoff from agricultural fields, and emissions of pollutants into the atmosphere.

The Shu-Talas River Basin. The basin is formed by the Shu, Talas and Asa rivers, and covers a total area of 64,300 km² (including part of Kyrgyzstan's territory). Most of the basin's territory (73 per cent) lies within desert and semi-desert zones, whilst the foothills of the Tien Shan mountain range account for 14 per cent of its area. The Shu-Talas river basin contains 224 small rivers (140 in the Shu river basin, 20 in the Talas river basin and 64 in the Asa river basin), as well as 35 lakes and 3 large reservoirs.

In the Shu-Talas basin, 75 per cent of river flow originates within the territory of the Kyrgyz Republic, and there is a very high pressure on water resources. 97 per cent of the total water abstracted is used for irrigation, where water losses during conveyance average 0.6 km³ of the total water abstracted. The Shu River, which is classified as Class 3 according to water quality standards, is subject to pollution from sulphates, nitrite nitrogen, total iron, copper, zinc and phenols (*Kontseptsiya razvitiya sistemy upravleniya vodnymi resursami...*, 2021).

In the Republic of Kazakhstan, the following key problems regarding the current state of the water sector can be identified: a shortage of high-quality drinking water; insufficient irrigation water during the growing season; the dependence of the environmental situation in transboundary water bodies on the water policies of neighbouring states (Central Asia, the People's Republic of China, the Russian Federation); the depletion of water bodies as a result of the irrational use of water resources; the dilapidated state of water management infrastructure and the associated massive losses; insufficient protection against floods and low water levels; and low volumes of recycled water (recycled for purification purposes) in industry.

In Kazakhstan, considerable attention is paid to water resources management policy, as, for various reasons, water resources are dwindling whilst the population and, consequently, water consumption are growing. The key policy directions for the sustainable use of water resources are set out in the adopted strategic policy documents and in water legislation.

The Water Code of the Republic of Kazakhstan, adopted in 2003, is the key piece of legislation governing water resources. The main principles of water legislation include prioritising the supply of drinking water to the population, ensuring fair and equal access to water for the population, as well as the integrated and rational use of water and the protection of water bodies. The main objectives of water legislation are: to achieve and maintain an environmentally safe and economically optimal level of water use and protection of water resources, as well as water supply and wastewater disposal, in order to preserve and improve the living conditions of the population and the environment. The Water Code addresses the following issues: the implementation of state policy in the field of the use and protection of water resources, water supply and wastewater disposal; the regulation of water relations; the provision of a legal framework to support and develop sustainable water use; the definition of the fundamental principles and directions for the use and protection of water resources; the management of relations concerning the study, exploration, rational and integrated use and protection of water resources, land reclamation systems and water management structures; the definition of directions for the development of land reclamation; and the protection of the population and economic facilities from emergencies at water management structures and the consequences caused by them (*Vodnyy kodeks Respubliki Kazakhstan...*, 2003).

In 2002, the 'Drinking Water' Sectoral Programme for 2002–2010 was adopted. The programme aims to ensure a sustainable supply of drinking water of guaranteed quality and in the necessary quantities to the population of the Republic of Kazakhstan (*Otraslevaya programma "Pit'yevaya voda"...*, 2002). As a result of the implementation of the 'Drinking Water until 2010' programme, drinking water supply networks have been constructed and renovated in the regions; water supply has been optimised and access to centralised water supply in rural settlements has been improved; and the number of water supply systems failing to meet sanitary standards has been reduced.

In 2014, the State Programme for Water Resources Management was adopted (now repealed). The main objective of the programme was to ensure Kazakhstan's water security by improving the efficiency of water resources management. The programme set out the following objectives: to guarantee the supply of water resources to the population, the environment and economic sectors by implementing water-saving measures and increasing the volume of available water resources; to improve the efficiency of water resources management; and to ensure the conservation of aquatic ecosystems. The programme provided for measures to reduce the projected water shortage by 2020 through the modernisation and development of infrastructure, the efficient use and management of water resources, and the modernisation of water supply and sanitation systems in settlements (*Gosudarstvennaya programma upravleniya vodnymi resursami...*, 2014).

A Presidential Decree in 2017 approved the State Programme for the Development of the Agro-Industrial Complex for the period 2017–2021, which included three target indicators relating to the water sector. These include: a 20 per cent reduction in irrigation water consumption per hectare of irrigated land compared with 2015 levels; an increase in the volume of water in industrial water recycling systems from 0.69 km³ in 2015 to 0.77 km³ in 2021, and in industrial water reuse systems from 7.3 km³ in 2015 to 7.62 km³ in 2021; an increase in additional surface water resources by 1.9 km³ by 2021 compared with 2015 levels (*Gosudarstvennaya programma razvitiya agropromyshlennogo kompleksa...*, 2018).

The 'Ak Bulak' programme for 2011–2020, which came to an end in 2014, was aimed at providing the population with high-quality drinking water and wastewater services. The main objectives were: the construction and refurbishment of centralised water supply and wastewater disposal systems in urban areas and rural settlements, and ensuring the efficient and cost-effective operation of water supply and wastewater disposal systems in these settlements (*Otraslevaya programma "Pit'yevaya voda"...*, 2002).

As a result of the work carried out, 1,128 km of water supply networks were reconstructed and laid, and the water supply was improved in 178 settlements with a total population of 398,000 people. Between 2012 and 2014, 557 rural settlements were surveyed and groundwater reserves totalling 252,200 m³/day were approved. Between 2011 and 2014, 1,312 water supply and sanitation projects were implemented. As a result, access to centralised water supply in urban and rural settlements increased (*Programma "Aq bulaq"...*, 2011).

The State Programme for Regional Development up to 2020, developed as part of the implementation of the Strategic Development Plan of the Republic of Kazakhstan up to 2025, aims, amongst other things, to ensure the rational provision of high-quality drinking water and wastewater services to the population. As a result of the programme, 6,167 km of water supply and wastewater networks have been constructed and upgraded (*Gosudarstvennaya programma razvitiya regionov...*, 2018).

In 2015, the 'Nurly Zhol' State Infrastructure Development Programme for 2015–2019 was adopted. Among other things, one of the programme's main objectives is the modernisation (reconstruction and construction) of water supply and wastewater disposal infrastructure (*Gosudarstvennaya programma infrastruktturnogo razvitiya "Nurly zhol"...*, 2015).

The Republic of Kazakhstan has adopted the State Programme for Water Resources Management in the Republic of Kazakhstan up to 2030, which aims to guarantee the supply of water resources for the country's sustainable development, and to conserve and restore water bodies to a state that ensures environmentally favourable conditions for the population and the economy.

This strategic programme is an important document setting out 10 key areas of water resources management: effective international cooperation; improvement of the legal framework; institutional reform; modernisation and reconstruction of regional water

management infrastructure; research into international experience in establishing a water market; the digitalisation of the water sector, the implementation of the 'Smart Water' project, the environmentally sound use of water resources, the training of specialists with the skills required to work in the modern water sector, and the implementation of national water projects (*Gosudarstvennaya programma upravleniya vodnymi resursami...*, n.d.).

Seven of Kazakhstan's eight river basins are transboundary watercourses. Population growth and economic development have significantly increased water demand. Due to the intensification of ever-increasing human pressure, a complex situation has arisen on many of Kazakhstan's transboundary rivers. Among the largest rivers in Kazakhstan of transnational importance are: the Syr Darya and Amu Darya (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan), the Shu and Talas (Kyrgyzstan and Kazakhstan), the Ili (PRC, Kazakhstan), the Irtysh (PRC, Kazakhstan, Russia), the Ural, the Esil and the Tobyl (Kazakhstan, Russia). Of paramount importance are the Caspian and Aral Seas, Lakes Issyk and Balkhash, as well as other natural water bodies and major reservoirs in the basins of the Syr Darya, Amu Darya and Irtysh rivers (Musina, 2016).

Kazakhstan is heavily dependent on the water management policies of its neighbouring countries. In this regard, the most vulnerable are the Aral-Syr Darya (91 per cent), Ural-Caspian (82 per cent), Shu-Talas (74 per cent) and Balkhash-Alakol (48 per cent) water basins, whilst the Tobyl -Torgay (12 per cent) and Irtysh (20 per cent) water basins are the least vulnerable. Compared with 2019 levels, inflow from outside the country, taking into account an anthropogenic reduction of 17.2 km³ in transboundary rivers, amounted to 51.5 km³. In the Aral-Syr Darya catchment area – the one with the most strained water balance – the reduction reached 38 per cent (10.2 km³) from Uzbekistan; in the Shu-Talas catchment area, it was 32 per cent (1.3 km³) from Kyrgyzstan; from the PRC, flow along the Irtysh decreased by 21.5 per cent (2.1 km³), and in the Ural-Caspian basin by 15 per cent (1.3 km³); in the Balkhash-Alakol basin, river inflow decreased by 15.3 per cent (2.3 km³) due to human activities within China. Taking forecasts into account, by 2030 the reduction in transboundary flow will amount to 5 km³ (*Kontseptsiya razvitiya sistemy upravleniya vodnymi resursami...*, 2021).

Kazakhstan actively participates in international cooperation on water issues and has ratified the Convention on the Protection and Use of Transboundary Watercourses and International Lakes, under which the Parties shall cooperate on the basis of equality and reciprocity by concluding bilateral and multilateral agreements with a view to developing coordinated policies, programmes and strategies covering the relevant catchment areas or parts thereof, to ensure and minimise transboundary impacts and to protect the environment of transboundary waters. Kazakhstan also acts as a 'stabilising factor' for regional cooperation among the countries of Central Asia and takes an active part in activities under the Convention on Transboundary Waters (*O prisoyedinenii Respubliki Kazakhstan k Konventsii...*, 2000). Significant achievements in the field of transboundary water cooperation include the conclusion of two bilateral agreements with the Russian Federation (2010 and 2016) and a bilateral agreement on water quality with the People's Republic of China (2011). However, Kazakhstan's bilateral cooperation on water resources does not yet cover transboundary groundwater (United Nations, 2019).

In the Republic of Kazakhstan, water consumption is rising across all sectors of the economy, averaging 25.7 km³ per year, 95 per cent of which comes from surface water. Breaking down water consumption by sector: agriculture accounts for over 60 per cent, industry for over 20 per cent, whilst 4–5 per cent of total water abstraction is used annually for domestic and household purposes. The supply of water to the population for drinking and domestic purposes does not exceed 5 per cent annually. The security of the water supply depends on the level of water consumption across various economic sectors, as well as on the effective implementation of policies for the rational use of water resources and the prevention of water pollution. Furthermore, water losses are inevitable; during transmission, these amount on average to around

60 per cent of water consumption for agricultural users, around 40 per cent for industrial production and 50 per cent for municipal services. If current trends in water consumption in the utilities sector, agriculture and industry continue, water abstraction is expected to rise to 29.7 km³ per year by 2040 (Ministry of Ecology, Geology and Natural Resources of the Republic of Kazakhstan. (2021). *National report on the state of the environment and the use of natural resources of the Republic of Kazakhstan for 2020*).

A comparison of water resources in different years of water supply with the needs of Kazakhstan's economy shows that there is an acute water shortage both in individual regions and across the country as a whole. The water deficit reaches 6.6 km³ in years of average water availability and is evident in all river basins. In years of low water availability, the water supply level stands at 60 per cent, and in some regions (Central Kazakhstan) at just 5–10 per cent; the shortfall mainly affects irrigated agriculture.

The causes of the water shortage include natural factors (the uneven distribution of surface water across the country, and significant seasonal and inter-annual fluctuations in river flow), significant utilisation of transboundary river flows by neighbouring states, the over-use of non-renewable water for irrigation within the country and water losses, as well as the poor quality of the water consumed, all of which contribute to the under-utilisation of available water resources (Programma razvitiya OON. (2004). *Vodnyye resursy Kazakhstana v novom tysyacheletii*).

Climate change may result in a reduction in water resources, which poses a threat to the country's sustainable development. Furthermore, transboundary rivers may experience water shortages due to the unsustainable use of water resources in neighbouring countries.

The following approaches can be taken to address water shortages in the republic. The first approach is to reduce the anthropogenic pressure on water resources, which involves implementing measures to reduce water consumption and applying the best available technologies for the rational use of fresh water in industry, agriculture and the utilities sector. The second approach is to increase freshwater resources through long-term and seasonal regulation of river flows; the use of groundwater resources; desalination of saline water; and the territorial redistribution of water resources (Toleubayeva, 2012).

To address water-related issues in Kazakhstan, it is necessary to: improve water management policy, ensure the rational use and protection of water resources, resolve issues concerning the use of transboundary water resources, taking into account the interests of all parties; develop an effective water-use system with minimal wastage; improve the quality of drinking water at regional and local levels; and address the deterioration of water management infrastructure.

Conclusion

Water resources are one of the key elements of sustainable development in the Republic of Kazakhstan, playing a vital role in its social, economic and environmental aspects. The quality and quantity of water resources are the main criteria for the country's development, upon which the health and well-being of the population directly depend.

Kazakhstan has adopted the river basin management approach. There are eight river basins within the country, seven of which are transboundary watercourses. Each basin faces environmental challenges linked to industrial pollution, the unsustainable use of water resources, and the uneven distribution of flow from neighbouring states.

Common challenges in the field of water resources in the Republic of Kazakhstan include: a decline in water resources, the inefficient use and uneven distribution of water in transboundary basins, and a deterioration in water quality.

To address water supply issues in Kazakhstan, the following programmes have been implemented consecutively since 2002: the 'Drinking Water' Sectoral Programme for 2002–2010,

the 'State Programme for Water Resources Management', the 'State Programme for the Development of the Agro-Industrial Complex for the period 2017–2021', the 'Ak Bulak Programme for 2011–2020', the 'State Programme for Regional Development up to 2020', the 'Nurly Zhol' State Programme for Infrastructure Development for 2015–2019 and the 'State Programme for Water Resources Management in the Republic of Kazakhstan until 2030.

The main water consumers in the Republic of Kazakhstan are: agriculture, industry and the utilities sector. Water consumption is expected to rise in the future; therefore, the prospects for the development of industry, agriculture and the utilities sector are linked to a reduction in water use through the introduction of Best Available Techniques (BAT) and water recycling systems.

Overcoming the water crisis requires improvements to the system of water resources management and water use, which is one of the key priorities of the Republic of Kazakhstan's state policy, whose strategic objective is to implement long-term, comprehensive measures aimed at eliminating the negative consequences of water scarcity and creating conditions for economic growth, addressing social and environmental issues, as well as regulating inter-state water relations.

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Technical Sciences

Blockchain in the Internet of Things (IoT): Modern Trends, Opportunities, and Future Development

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Abstract

The rapid development of the Internet of Things (IoT) has resulted in the emergence of billions of interconnected devices that continuously generate massive volumes of data. One of the major challenges associated with this growth is ensuring data security, integrity, trust between devices, and the scalability of the entire infrastructure. Blockchain technology has emerged as one of the most promising solutions to these challenges. Through decentralized data storage, cryptographic protection, and the elimination of centralized control, blockchain significantly enhances the resilience of IoT systems against cyberattacks, hardware failures, and data manipulation.

This paper examines contemporary approaches to integrating blockchain technology with the Internet of Things, discusses the major benefits and current limitations of this integration, and analyzes its practical applications across various sectors of the digital economy. Furthermore, the study highlights future research directions involving the convergence of blockchain, edge computing, artificial intelligence, and next-generation communication networks.

Keywords: Internet of Things, IoT, blockchain, distributed ledger, smart contracts, cybersecurity, Edge Computing, artificial intelligence.

Introduction

The Internet of Things (IoT) has become one of the fastest-growing technologies driving the digital transformation of modern society. IoT technologies are currently employed in numerous sectors, including manufacturing, healthcare, transportation, agriculture, logistics, energy management, and smart city infrastructures. According to recent industry reports, tens of billions of connected devices are already operating worldwide, with this number expected to continue increasing significantly over the coming years.

The rapid expansion of IoT ecosystems has led to an unprecedented growth in the amount of generated data. Consequently, ensuring secure communication, reliable data storage, efficient processing, and scalable infrastructure has become increasingly important. Traditional cloud-centric architectures, where all information is transmitted to centralized data centers for processing, are gradually reaching their practical limitations. Such architectures often suffer from increased network latency, excessive bandwidth consumption, higher operational costs, and the existence of single points of failure.

To address these challenges, modern distributed computing paradigms—including Edge Computing and Fog Computing—have gained considerable attention. These approaches move computational resources closer to data sources, reducing latency while improving system responsiveness and bandwidth utilization. Within this decentralized computing environment,

blockchain technology has emerged as a fundamental component for establishing trusted interactions among heterogeneous IoT devices.

Blockchain is a decentralized distributed ledger that records transactions in a secure, transparent, and tamper-resistant manner. Unlike traditional centralized databases, blockchain eliminates the need for a trusted intermediary by enabling network participants to validate transactions collectively through consensus mechanisms. This capability makes blockchain particularly attractive for IoT environments, where devices manufactured by different vendors often need to exchange information securely without relying on a centralized authority.

The integration of blockchain and IoT offers numerous advantages, including improved cybersecurity, enhanced data integrity, decentralized identity management, automated execution of smart contracts, and transparent auditability of device interactions. These characteristics enable the development of autonomous cyber-physical systems capable of making reliable decisions with minimal human intervention.

However, despite its significant potential, blockchain implementation in IoT environments also faces several technical challenges. These include scalability limitations, transaction throughput constraints, energy consumption associated with certain consensus algorithms, interoperability among heterogeneous platforms, and the limited computational capabilities of many IoT devices.

The purpose of this paper is to examine the role of blockchain technology in modern IoT ecosystems, analyze its key advantages and existing limitations, review practical implementation scenarios across various industries, and discuss future directions for the evolution of decentralized intelligent systems.

The Role of Blockchain in the Internet of Things

The rapid expansion of the Internet of Things has fundamentally transformed the way data are generated, transmitted, and processed. Billions of interconnected sensors, controllers, embedded systems, and intelligent devices continuously exchange information to support industrial automation, healthcare services, transportation systems, environmental monitoring, and smart city infrastructures. As IoT networks become increasingly complex, traditional centralized architectures encounter significant technical and security challenges that limit their efficiency and scalability.

Most existing IoT platforms rely on centralized cloud infrastructures in which all devices communicate with a central server responsible for authentication, data storage, processing, and decision-making. Although this architecture simplifies system management, it introduces several critical limitations.

First, centralized systems create a single point of failure. A malfunction, cyberattack, or service outage affecting the central server may disrupt the operation of the entire IoT network. Second, transmitting massive volumes of sensor data to remote cloud data centers increases communication latency and places heavy demands on network bandwidth. These delays are particularly problematic in real-time applications such as autonomous transportation, industrial automation, and emergency response systems.

Another major concern is cybersecurity. As the number of connected devices continues to grow, IoT ecosystems become increasingly attractive targets for cybercriminals. Weak authentication mechanisms, outdated firmware, insecure communication protocols, and poorly protected devices have contributed to numerous large-scale attacks involving IoT botnets. Compromised devices may be exploited to launch distributed denial-of-service (DDoS) attacks, manipulate sensor readings, or gain unauthorized access to critical infrastructure.

Blockchain technology provides an alternative decentralized model capable of addressing many of these challenges. Instead of relying on a central authority, blockchain distributes transaction records across multiple network nodes. Every transaction is cryptographically verified,

timestamped, and permanently recorded within the distributed ledger, making unauthorized modification virtually impossible.

Within IoT ecosystems, blockchain serves as a trusted infrastructure that enables secure interactions among devices without requiring mutual trust between participants. Every device can possess a unique cryptographic identity represented by public and private key pairs. This decentralized identity allows devices to authenticate one another securely while maintaining data integrity and confidentiality.

One of the most valuable capabilities of blockchain is the implementation of smart contracts. Smart contracts are self-executing software programs stored on the blockchain that automatically perform predefined actions when specified conditions are satisfied. They eliminate the need for intermediaries while reducing operational costs and minimizing human error.

For example, an industrial sensor may automatically initiate a maintenance request when measured vibration levels exceed an established threshold. A smart contract can verify the sensor readings, notify maintenance personnel, order replacement components, and record every operation within the blockchain without manual intervention.

Similarly, in smart energy systems, blockchain-based smart contracts enable peer-to-peer electricity trading. Households equipped with renewable energy sources, such as solar panels, can automatically sell surplus electricity to neighboring consumers. Payments are executed immediately after energy delivery is confirmed by smart meters, creating an efficient decentralized energy marketplace.

Blockchain also enhances trust in collaborative IoT environments where devices belong to different organizations. Since all transactions are transparently recorded and independently verified by network participants, organizations can exchange information without relying on centralized intermediaries. This capability is particularly valuable in supply chain management, healthcare information systems, financial services, and international logistics.

Another significant advantage is data integrity. Sensor measurements stored on the blockchain cannot be altered retroactively without network consensus. Consequently, organizations can verify that collected information has not been modified after its original recording. Such immutability is especially important for medical records, pharmaceutical manufacturing, industrial quality assurance, environmental monitoring, and legal compliance.

Blockchain further supports decentralized access control. Rather than depending on centralized authentication servers, access permissions can be managed through cryptographic credentials and smart contracts. This approach improves both security and operational flexibility while reducing administrative overhead.

Nevertheless, integrating blockchain with IoT also introduces technical challenges. Conventional public blockchain networks often experience limited transaction throughput and relatively high confirmation times, making them unsuitable for processing millions of sensor-generated events per second. Consequently, many practical IoT deployments employ permissioned blockchain platforms or lightweight distributed ledger technologies optimized for industrial applications.

To improve performance, blockchain is increasingly combined with Edge Computing and Fog Computing architectures. Instead of transmitting every sensor reading directly to the blockchain, nearby edge servers perform preliminary filtering, aggregation, and analytics. Only critical events, security logs, or verified transactions are subsequently recorded in the distributed ledger. This layered architecture significantly reduces network traffic, decreases latency, and improves the scalability of large IoT deployments.

Recent advances in blockchain research have also focused on energy-efficient consensus mechanisms such as Proof of Stake (PoS), Proof of Authority (PoA), and Practical Byzantine Fault Tolerance (PBFT). Compared with the computationally intensive Proof of Work algorithm, these

approaches provide higher transaction throughput while substantially reducing energy consumption, making them more suitable for IoT environments.

Overall, blockchain is evolving from a financial technology into a universal trust infrastructure for distributed cyber-physical systems. Its ability to provide decentralized identity management, secure data sharing, automated decision-making, and immutable transaction records positions blockchain as a key enabling technology for the next generation of intelligent IoT ecosystems.

Advantages and Modern Architecture of Blockchain-Based IoT Systems

The convergence of blockchain technology and the Internet of Things represents one of the most significant developments in modern distributed computing. While IoT provides continuous data collection and real-time interaction between physical devices, blockchain establishes a trusted decentralized infrastructure for secure communication, transaction validation, and data management. Together, these technologies form the foundation for autonomous cyber-physical systems capable of operating with minimal human intervention.

Key Advantages of Blockchain in IoT

The integration of blockchain into IoT ecosystems provides numerous technological and organizational benefits.

Enhanced Security

Security remains one of the greatest challenges facing IoT networks. Many connected devices possess limited computational resources and cannot implement sophisticated security mechanisms. Consequently, attackers frequently exploit weak authentication methods, outdated firmware, and insecure communication protocols.

Blockchain addresses these vulnerabilities through public-key cryptography, decentralized authentication, and immutable transaction records. Every participating device can be assigned a unique cryptographic identity, allowing secure authentication without relying on centralized identity providers. Since every transaction is digitally signed and verified by network participants, unauthorized data modification becomes extremely difficult.

Data Integrity and Traceability

IoT applications often generate critical operational data whose authenticity must be preserved throughout the entire lifecycle.

Blockchain guarantees data integrity by storing cryptographic hashes of transactions within immutable blocks. Once information has been validated and added to the distributed ledger, altering or deleting records without network consensus becomes practically impossible.

Furthermore, blockchain creates a complete audit trail of every transaction, allowing organizations to trace the origin, ownership, and modification history of assets, devices, and sensor measurements.

Elimination of Single Points of Failure

Traditional cloud-based IoT architectures depend heavily on centralized servers responsible for device authentication, data storage, and application management. Failure of these servers—whether due to hardware malfunction, software errors, or cyberattacks—can interrupt the operation of the entire system.

Blockchain distributes identical copies of the ledger across multiple network nodes. Consequently, the failure of individual nodes does not compromise the availability or integrity of the entire infrastructure. This decentralized architecture significantly improves system resilience and fault tolerance.

Automation through Smart Contracts

Smart contracts extend blockchain functionality beyond secure data storage by enabling autonomous execution of predefined business rules.

Instead of relying on manual verification or centralized software services, smart contracts automatically perform transactions once specified conditions are satisfied. Examples include automated equipment maintenance scheduling, digital identity verification, insurance claim processing, energy trading, and supply chain management.

Automation reduces administrative costs, accelerates business processes, and minimizes the possibility of human error.

Transparency and Trust

Organizations increasingly collaborate within distributed digital ecosystems involving manufacturers, suppliers, logistics providers, financial institutions, and regulatory agencies.

Blockchain enables all authorized participants to access identical verified transaction records. Since no participant can modify historical information independently, blockchain establishes a trusted environment even among organizations that do not maintain direct business relationships.

This transparency improves regulatory compliance, simplifies auditing procedures, and increases confidence in shared digital infrastructures.

Modern Blockchain-IoT Architecture

Current blockchain-enabled IoT systems typically employ a multilayer architecture designed to optimize performance, scalability, and security.

Device Layer

The lowest layer consists of physical IoT devices responsible for collecting environmental information and interacting with the surrounding environment.

Typical devices include:

- environmental sensors;
- industrial controllers;
- smart meters;
- wearable medical devices;
- surveillance cameras;
- autonomous robots;
- connected vehicles;
- household appliances.

Most devices possess limited processing power and battery capacity, making it impractical for them to execute full blockchain protocols independently.

Edge Computing Layer

To overcome resource limitations, modern IoT architectures employ Edge Computing.

Edge nodes are geographically located close to data sources and perform preliminary processing before transmitting information to higher network layers.

Typical edge computing functions include:

- data aggregation;
- anomaly detection;
- local artificial intelligence inference;
- protocol conversion;
- encryption;
- temporary data storage;
- blockchain gateway services.

Processing data near its source substantially reduces communication latency and decreases bandwidth consumption.

Blockchain Layer

The blockchain layer forms the trust infrastructure of the entire ecosystem.

Its primary responsibilities include:

- decentralized identity management;

- transaction validation;
- immutable data storage;
- execution of smart contracts;
- distributed access control;
- audit logging.

Depending on application requirements, organizations may deploy either public, private, consortium, or hybrid blockchain platforms.

Industrial IoT systems frequently employ permissioned blockchains because they provide higher transaction throughput, lower latency, and stronger governance mechanisms than public blockchain networks.

Cloud and Artificial Intelligence Layer

Cloud platforms remain essential for long-term data storage, advanced analytics, machine learning, and enterprise resource planning.

Unlike traditional cloud-centric architectures, however, only processed or strategically important information is transmitted to cloud services.

Artificial intelligence algorithms analyze historical blockchain records together with real-time IoT data to perform:

- predictive maintenance;
- anomaly detection;
- demand forecasting;
- quality control;
- intelligent resource allocation;
- cybersecurity monitoring.

This combination of blockchain, AI, and IoT enables organizations to create highly autonomous intelligent systems capable of continuous self-optimization.

Integration with Emerging Technologies

Modern blockchain-IoT ecosystems increasingly incorporate several complementary technologies.

Artificial Intelligence

Artificial intelligence enhances blockchain-enabled IoT systems by analyzing trusted datasets whose authenticity has been verified through blockchain.

Machine learning models can accurately predict equipment failures, detect abnormal network behavior, optimize energy consumption, and improve industrial productivity.

Digital Twins

Digital Twin technology creates virtual representations of physical assets that continuously synchronize with real-world sensor data.

Blockchain provides secure storage of operational history, maintenance records, software updates, and ownership information associated with each digital twin.

This capability supports predictive maintenance and lifecycle management while improving operational transparency.

Fifth- and Sixth-Generation Communication Networks

The deployment of 5G and future 6G communication networks significantly expands blockchain-IoT capabilities.

Ultra-low latency, high bandwidth, and massive machine-type communication allow billions of connected devices to exchange information in real time.

These communication technologies complement Edge Computing by supporting distributed intelligence and enabling decentralized industrial automation at unprecedented scales.

Scalability Considerations

Although blockchain provides substantial security and transparency benefits, scalability remains an important research challenge.

Large industrial IoT deployments may generate millions of events every second, exceeding the processing capacity of conventional blockchain platforms.

Researchers are actively developing several approaches to address this limitation, including:

- sharding techniques;
- Layer-2 scaling solutions;
- sidechains;
- Directed Acyclic Graph (DAG)-based distributed ledgers;
- lightweight blockchain protocols for constrained IoT devices.

These innovations are expected to significantly improve transaction throughput while maintaining security and decentralization.

Overall, the modern Blockchain-IoT architecture represents a balanced combination of distributed computing, edge intelligence, cloud analytics, and cryptographic trust mechanisms. Rather than replacing cloud computing, blockchain complements existing infrastructures by providing secure decentralized coordination among heterogeneous intelligent devices.

Practical Applications and Current Challenges of Blockchain-IoT Systems

The integration of blockchain technology with the Internet of Things has moved beyond theoretical research and is increasingly being implemented across various sectors of the digital economy. Advances in distributed ledger technologies, edge computing, artificial intelligence, and high-speed communication networks have enabled the development of secure, decentralized, and autonomous IoT ecosystems. Today, Blockchain-IoT solutions are being adopted in manufacturing, logistics, healthcare, agriculture, energy, transportation, and smart city infrastructures.

Industrial Internet of Things (IIoT)

One of the most mature application areas of Blockchain-IoT is the Industrial Internet of Things (IIoT), which forms the technological foundation of Industry 4.0 and the emerging Industry 5.0 paradigm.

Modern manufacturing facilities employ thousands of sensors that continuously monitor machine performance, environmental conditions, production quality, and equipment status. These sensors generate enormous volumes of operational data that support predictive maintenance and intelligent process optimization.

Blockchain enhances industrial IoT by providing immutable records of equipment operation, maintenance history, software updates, and quality inspections. Since production data cannot be modified retroactively, manufacturers obtain reliable evidence for regulatory compliance, product certification, and warranty management.

Furthermore, blockchain enables secure collaboration among manufacturers, suppliers, logistics providers, and customers without requiring centralized databases. Smart contracts can automatically initiate maintenance requests, verify product authenticity, or authorize payments once contractual conditions are fulfilled.

Supply Chain Management

Supply chain management represents one of the most successful commercial applications of blockchain technology.

Global supply chains involve numerous independent organizations responsible for manufacturing, transportation, warehousing, customs clearance, and retail distribution. Maintaining transparency across these complex processes remains a significant challenge.

IoT devices—including RFID tags, GPS trackers, temperature sensors, humidity monitors, and environmental detectors—continuously collect information regarding product location and transportation conditions.

Blockchain records these data in a tamper-resistant distributed ledger, allowing every authorized participant to verify product history throughout its lifecycle.

This approach provides several important benefits:

- prevention of counterfeit products;
- end-to-end product traceability;
- automated customs documentation;
- verification of cold-chain conditions;
- improved food safety;
- enhanced pharmaceutical logistics;
- increased consumer confidence.

Recent international standardization efforts have highlighted blockchain-enabled traceability as a major application area for IoT, particularly in agriculture, food production, and asset tokenization.

Smart Cities

The concept of Smart Cities depends heavily on interconnected IoT infrastructures that support transportation, public safety, utilities, environmental monitoring, and municipal services.

Blockchain improves smart city operations by enabling secure data sharing among government agencies, utility providers, transportation operators, and citizens.

Typical Blockchain-IoT applications include:

- intelligent traffic management;
- smart parking systems;
- adaptive street lighting;
- waste collection optimization;
- environmental monitoring;
- digital identity services;
- public infrastructure maintenance.

Because blockchain provides transparent and immutable records, municipalities can improve accountability while reducing opportunities for fraud and unauthorized data manipulation.

Healthcare

Healthcare is another sector where Blockchain-IoT technologies offer considerable benefits.

Wearable medical devices continuously monitor physiological parameters such as heart rate, blood pressure, blood glucose levels, oxygen saturation, and body temperature.

These measurements are transmitted to healthcare providers for diagnosis and remote patient monitoring.

Blockchain ensures that medical records remain authentic, confidential, and resistant to unauthorized modification.

Smart contracts can automatically grant physicians temporary access to patient records while maintaining complete audit logs of every access request.

Such systems improve patient privacy, simplify medical data exchange among hospitals, and reduce administrative complexity.

Smart Energy Systems

Modern electrical grids increasingly incorporate distributed renewable energy resources, including solar panels, wind turbines, and battery storage systems.

Blockchain enables decentralized energy markets where households and businesses can exchange electricity directly without traditional intermediaries.

Smart meters equipped with IoT sensors measure energy production and consumption in real time.

Smart contracts automatically calculate payments, validate transactions, and execute financial settlements after electricity delivery is confirmed.

This decentralized model improves energy efficiency while supporting the transition toward sustainable energy ecosystems.

Intelligent Transportation Systems

Connected and autonomous vehicles rely extensively on real-time communication with surrounding infrastructure.

Vehicles continuously exchange information concerning traffic conditions, road hazards, navigation, weather, and vehicle status.

Blockchain provides secure storage of vehicle maintenance records, software updates, accident histories, ownership information, and autonomous driving logs.

This capability increases trust among manufacturers, insurance companies, transportation authorities, and vehicle owners.

Future intelligent transportation systems are expected to integrate blockchain with Vehicle-to-Everything (V2X) communication technologies to enable secure decentralized mobility services.

Smart Agriculture

Agriculture has become another important application domain for Blockchain-IoT technologies.

IoT sensors monitor soil moisture, temperature, rainfall, crop health, irrigation systems, fertilizer usage, and livestock conditions.

Blockchain securely records agricultural data, allowing farmers, distributors, certification agencies, and consumers to verify product origin and cultivation practices.

Such transparency supports food safety regulations, organic certification, and sustainable agricultural management.

International telecommunications standards have recently identified blockchain-enabled precision agriculture as one of the key future use cases for IoT ecosystems.

Current Challenges

Despite considerable technological progress, several important challenges continue to limit widespread adoption of Blockchain-IoT systems.

Scalability

Large IoT deployments may generate millions of transactions every second.

Current blockchain platforms often cannot process such transaction volumes without introducing delays or increasing operational costs.

Researchers are actively investigating Layer-2 protocols, sharding, sidechains, and lightweight distributed ledger technologies to improve scalability.

Resource Constraints

Many IoT devices possess limited computational resources, memory capacity, and battery life.

Consequently, executing complete blockchain protocols directly on resource-constrained sensors remains impractical.

Hybrid architectures combining Edge Computing with blockchain have therefore become the preferred implementation strategy.

Interoperability

IoT ecosystems incorporate devices produced by numerous manufacturers using different communication protocols and data formats.

Developing universal interoperability standards remains one of the major challenges facing both academia and industry.

Current international standardization initiatives continue to address interoperability between blockchain platforms and heterogeneous IoT infrastructures.

Privacy Protection

Although blockchain improves transparency, some applications require strict confidentiality.

Medical records, financial transactions, industrial trade secrets, and personal information cannot always be stored directly on public distributed ledgers.

Consequently, modern systems increasingly employ permissioned blockchains, off-chain storage mechanisms, zero-knowledge proofs, and advanced cryptographic techniques to balance transparency with privacy.

Regulatory and Legal Issues

Legal frameworks governing blockchain technology continue to evolve across different jurisdictions.

Questions concerning digital identity, cross-border data sharing, smart contract enforceability, and data ownership require further regulatory clarification before Blockchain-IoT systems achieve widespread global deployment.

Overall, despite these technical and organizational challenges, recent research demonstrates that blockchain remains one of the most promising technologies for building secure, decentralized, and trustworthy IoT ecosystems capable of supporting next-generation digital infrastructures.

Conclusion

The integration of blockchain technology with the Internet of Things (IoT) has emerged as a promising approach for building secure, decentralized, and intelligent digital ecosystems. As IoT networks continue to expand, traditional centralized architectures face increasing challenges related to scalability, security, reliability, and trust. Blockchain addresses these issues by providing decentralized identity management, immutable data storage, secure communication, and automated execution of smart contracts.

This paper has shown that combining blockchain with Edge Computing, Artificial Intelligence, and cloud technologies enables the development of autonomous cyber-physical systems capable of efficient and trustworthy operation. Such integration enhances data integrity, transparency, and resilience while supporting applications in Industry 4.0, smart cities, healthcare, energy systems, transportation, and supply chain management.

Despite its significant potential, several challenges remain, including scalability, interoperability, privacy protection, and resource constraints of IoT devices. Ongoing research on lightweight consensus algorithms, Layer-2 solutions, permissioned blockchains, and edge intelligence is expected to overcome many of these limitations.

Overall, blockchain is evolving beyond its original role in cryptocurrencies to become a fundamental trust infrastructure for next-generation IoT systems. Continued advances in distributed ledger technologies and intelligent networking are expected to accelerate the adoption of secure, scalable, and autonomous IoT ecosystems across a wide range of industrial and societal applications.

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Psychological Sciences

PSYCHOLOGICAL CHARACTERISTICS OF CHILDREN EXPOSED TO VIOLENCE

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Abstract

The family plays an irreplaceable role in a child's development, personality formation, and overall well-being. It is within the family that children are expected to experience love, security, care, and emotional support. Moreover, the family is the primary environment where children learn interpersonal relationships and develop into responsible members of society. The experiences gained during childhood often influence an individual throughout life.

Unfortunately, many children are deprived of such care and are instead exposed to various forms of violence within their own families. Child abuse and violence have become some of the most serious social problems of our time. Children who experience violence often face difficulties in social adaptation and are at increased risk of developing psychological disorders. This article examines the main types of violence against children and explores the psychological characteristics and consequences observed in children who have been subjected to abuse.

Keywords: physical violence, sexual violence, psychological violence, trauma, abuse

Children, as one of the most vulnerable groups in society, are at a particularly high risk of experiencing violence. Child abuse is generally classified into four main categories: physical, sexual, psychological, and emotional violence.

Physical violence refers to any intentional act that causes physical harm to a person under the age of 18. It includes slapping, choking, pushing, kicking, unlawful confinement, beating with belts or ropes, and inflicting injuries with heavy objects or sharp instruments. Physical abuse also involves forcing children to consume alcohol or drugs, administering poisonous substances or non-prescribed sedative medications, and attempting to drown them.

Sexual violence involves the exploitation of children by adults or other children for sexual gratification. It includes sexual intercourse, mutual masturbation, and other forms of sexual contact. Sexual abuse also encompasses involving children in prostitution or the production of pornographic material, as well as secretly observing a child's intimate body parts while they are undressing or attending to personal hygiene.

Psychological violence refers to the persistent humiliation, intimidation, verbal abuse, rejection, and unjust blaming of a child by parents, caregivers, or other adults. It also includes the continuous use of deception, which undermines a child's trust in adults, as well as imposing responsibilities that are inappropriate for the child's age and developmental level (1, p. 51).

Emotional violence is considered by many specialists to be the underlying component of all forms of child abuse. Ignoring or rejecting a child's emotional and developmental needs can seriously hinder healthy personality development and emotional well-being.

Children who experience abuse or neglect often suffer psychological trauma that leaves lasting effects on their emotional functioning, behaviour, and interpersonal relationships throughout their lives.

The severity of the consequences of physical and sexual abuse depends on several factors, including the child's age, developmental stage, personal characteristics, and the frequency and intensity of the abuse. When violence causes severe pain or psychological trauma, its long-term effects become even more serious. Sexual abuse involving sexual intercourse is generally associated with the most severe outcomes. However, if the abuse is disclosed and the child's parents provide protection, emotional support, and validation, the child is more likely to recover from the traumatic experience successfully (3).

According to A. Green, both physical and sexual abuse may lead to the development of post-traumatic stress disorder (PTSD). Children who have experienced abuse may suppress or forget these traumatic memories during childhood, but they may later recover them in adulthood, particularly during the course of psychotherapy.

Children who have experienced violence often demonstrate the following psychological reactions and attitudes toward abuse:

- Feelings of responsibility for the violence: Children may believe that the abuse occurred because of their own behaviour, thinking, "If I had been a better child, my parents would not have hurt each other or me."
- Persistent feelings of guilt: They frequently blame themselves for repeated incidents of violence, even when they bear no responsibility.
- Hypervigilance: Even in calm and safe environments, children may remain constantly alert and may display sudden outbursts of aggression without any apparent trigger.
- Anxiety related to loss: Children who have been separated from abusive parents often experience a profound sense of loss. They worry not only about losing the familiar environment in which they lived but also about losing the positive image they had of their parents.
- Emotional ambivalence: Children often struggle to understand that people can experience conflicting emotions simultaneously. Therefore, when they say, "I don't know how to feel about this," they are not avoiding the conversation; rather, they are experiencing genuine emotional conflict.
- Fear of abandonment: Children removed from an abusive parent frequently fear that the remaining parent may also abandon them or die. As a result, they often become extremely dependent on the non-abusive parent and resist separation from them.
- Feelings of shame: Particularly among older children, experiences of abuse are commonly accompanied by intense feelings of shame.
- Anxiety about the future: The insecurity children experience in everyday life may lead them to believe that their future will also be filled with uncertainty and unexpected negative events.
- Low self-esteem: One of the most common psychological consequences of all forms of violence is diminished self-esteem. Low self-esteem contributes to both the development and persistence of mental health problems. Children with poor self-worth often experience guilt, shame, feelings of inadequacy, and worthlessness. They may believe that they are "worse than everyone else," making it difficult to build trusting relationships and interact successfully with their peers.

Low self-esteem may also function as a psychological defence mechanism in children exposed to violence. Externalising behaviours include complaining, an excessive desire to win at any cost, attempting to prove oneself through dishonest behaviour during games, perfectionism, exaggerated self-confidence, giving away personal belongings such as money, toys, or sweets to gain acceptance, blaming others for every problem, an excessive desire to possess material objects, and engaging in attention-seeking behaviours such as clowning, provoking peers, antisocial behaviour, stealing, lying, and arguing. Internalising behaviours include excessive self-criticism,

shyness, social withdrawal, constant apologising, fear of unfamiliar situations, and difficulty making or carrying out decisions (2, p. 335).

Victims of physical and sexual abuse frequently experience depression and are at an increased risk of engaging in self-destructive behaviours. Depressive symptoms may manifest as persistent sadness, irritability, emotional numbness, or an inability to experience joy and pleasure. Self-aggressive behaviours may include deliberate self-harm as well as suicide attempts.

Difficulty with self-regulation and behavioural problems are common characteristics of children who have experienced physical or sexual abuse. According to A. Green, aggressive and disruptive behaviour at home and at school, together with poor behavioural control, are among the most typical manifestations. Through aggressive behaviour, children attempt to protect themselves from overwhelming feelings of anxiety, fear, and helplessness. At the same time, these behaviours increase their emotional distance from others. Consequently, abused children often have few friends, as their peers tend to avoid them because of their impulsive and unpredictable behaviour. Children's and adolescents' responses to physical and sexual abuse vary according to their developmental stage:

- Children under three years of age commonly display fear, emotional confusion, loss of appetite, fear of strangers, aggression, and sleep disturbances.
- Preschool children usually exhibit relatively few psychosomatic symptoms; instead, emotional problems such as anxiety, fearfulness, shame, helplessness, and hostility are more frequently observed.
- Primary school-aged children may experience emotional ambivalence toward adults, difficulty understanding their role within the family, fear, shame, hostility, distrust of others, aggressive behaviour, social withdrawal or excessive talkativeness, disturbances in eating and sleeping patterns, feelings that their bodies are "contaminated," and inappropriate sexual behaviours toward other children.
- Children aged 9–13 years generally demonstrate the same behavioural and emotional difficulties observed in younger school-aged children. In addition, depression, oppositional behaviour, and attempts to manipulate other children for sexual purposes may also occur.
- Adolescents aged 13–18 years frequently experience hatred, guilt, shame, distrust, conflicting emotions toward adults, sexual dysfunction, uncertainty regarding their role within the family, feelings of worthlessness, suicidal behaviour, running away from home, aggression, and oppositional behaviour.

Children who have experienced abuse often rely on maladaptive psychological defence mechanisms. These defence mechanisms serve to protect them from painful emotions and overwhelming anxiety. Their primary function is to preserve the integrity of the self and reduce emotional distress. To cope with traumatic experiences, abused children commonly use psychological defences such as denial, projection, and isolation.

Victims of abuse often find it difficult to integrate both the positive and negative aspects of their parents' personalities. They make considerable efforts to preserve the image of a "good mother" or "good parent" and therefore tend to deny the reality of abuse when the abusive parent mistreats them. This reaction is particularly common among children whose mothers have lost parental rights because of alcohol dependence, child abuse, or neglect. Despite experiencing hunger, violence, and neglect, these children may still believe that living at home is preferable to being placed in residential care. Denial protects them from feelings of rejection and hatred toward their parents. Projection of their emotions and thoughts is often reflected in the games they create, the stories they tell, and the drawings they produce.

In summary, childhood exposure to violence may result in disturbances in self-concept, persistent feelings of guilt, depression, difficulties in interpersonal relationships, and sexual dysfunction later

in life.

Conclusion

The findings indicate that children who are exposed to violence frequently blame themselves for the abuse they experience. They often feel confused, ashamed, and emotionally distressed. When the perpetrator is a family member or someone close to the family, children are particularly reluctant to disclose the abuse because of fear, shame, or intimidation.

Exposure to violence commonly results in significant behavioural changes, including increased aggression, irritability, declining academic performance, depression, and suicidal tendencies. An important characteristic of these changes is that they often occur suddenly and are markedly different from the child's previous behaviour. Therefore, the appearance of such warning signs should alert parents, teachers, and mental health professionals to the possibility that the child may be experiencing abuse.

A child's sense of self-confidence, developed through early interactions with caregivers, has a profound influence on later psychological development. The quality of the relationship established with parents becomes the foundation for the child's future relationships with others. Children who experience verbal or physical abuse typically develop low self-esteem. When violence is inflicted by the very people whom the child trusts most, it causes deep psychological harm. As a result, the child may begin to distrust all interpersonal relationships, which hinders healthy personality development and increases vulnerability to future mental health disorders.

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Psychological characteristics of the digital generation: Self-boundaries and identity construction (Theoretical analysis in the context of various theories)

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Abstract. The formation of a digital society in modern times has had a serious impact on the development of socialization, self-expression and identity of young people. As a result of the fact that social media and other digital communication tools have become an integral part of everyday life, the boundaries of the self of individuals have expanded, and the interaction between the virtual and real environment has intensified. In this context, the identity of the digital generation is formed not only through traditional social activities, but also based on the feedback they receive based on their self-expression on digital platforms, social interaction and activities on social media accounts. The purpose of the presented thesis is to analyze the psychological characteristics of the digital generation formed in the new world, the transformation of self-boundaries and identity construction within the framework of an integrative theoretical approach. The analysis shows that the digital environment affects the development of the identity of young people in many ways. The study of this issue requires the integration of classical personality theories with modern digital psychology approaches. All this allows for a deeper understanding of the interrelationships between digital self-expression and identity development, as well as the formation of a theoretical basis for future empirical research.

Keywords: Digital generation, self-concept, extended self, identity, cyberpsychology

Introduction. In the modern era, the expansion of digital opportunities and people's rapid adaptation to these opportunities reveal a new direction of socialization, such as virtual socialization. People, especially young people, use the virtual space not only for communication, but also as a central space for self-expression, social acceptance, and self-searching. All this causes various changes in the development and socialization of their personality, leading to the emergence of a new concept of "virtual self". This process, in turn, expands the boundaries of psychological science and creates conditions for the emergence of a new field of it, such as cyberpsychology. In this direction, such changes in the development of personality and the study of the psychological mechanisms of virtual self-expression are of particular importance.

The satisfaction of one of the most important human needs, the need for socialization, has undergone various changes in our modern world with the capabilities of the digital environment. Socialization in virtual space differs from the real socialization environment. Here, the socialization process is not limited to the physical self directly in the social circle, but they can form their self in different forms in their virtual environment with different virtual accounts, avatars and various contents.

The importance of the topic is quite clear. In the current era, meeting the socialization needs of the new modern world is related to both real and virtual space. In this study, the issue of self-expression of the digital generation is analyzed not only in the humanistic and psychosocial concept, but also in the level of cyberpsychological realities. Here, Carl Rogers' concept of the self,

E. Erikson's identity theory and Russell Belkin's "Extended Self" model are integrated and personality transformations in the digital space are theoretically analyzed.

According to Erikson's theory of psychosocial development, the role of the social environment in a person's identity is very important. People build their identities with the social roles, expectations, and value systems they acquire in the social environment. This process is especially strengthened during adolescence and youth. Because every feedback from the social environment affects the development of the personality of that young individual. The impact of digital life on the pace of real life also changes this process considerably. In the current era, Erikson's theory of psychosocial development shows that the virtual environment acts as an alternative social space for the formation of human identity. It is also very important to analyze the issue from the Rogerian perspective. From Carl Rogers' ideas about the real and ideal self, as well as "self-attitude", it is clear to us that for the development of personality, there must be a correspondence between the elements we have listed. [4] According to his ideas, one of the main indicators of psychological health is authenticity. In the current era, the formation of the concept of the virtual self and the rapid adaptation of people to virtual life also affect this process. Thus, the virtual environment creates a new socialization opportunity for people, in which people can demonstrate characteristics that they cannot express in real life. In this case, the virtual environment can support authentic self-expression. On the other hand, in the virtual environment, individuals often create idealized images in order to be socially accepted and liked. This situation can lead to a difference between the real and virtual "I". Considering all this, when we analyze Rogers' approach from the Cyberpsychological perspective, we see that the psychological impact of digital self-expression depends on the extent to which that individual is authentic. Therefore, digital platforms can both strengthen authentic self-expression and create conditions for the creation of idealized identities.

The topic needs to be analyzed in the direction of Russell Belkin's "Extended Self" theory. According to his ideas, according to his theory, a person does not limit himself only to his physical body and mind; everything we own - things, brands, places and social media accounts - is part of our identity. We are "what we have," and objects reflect our identity. [1] Belkin's theory is adapted to the digital age, showing that social media accounts, digital images, avatars, and other digital objects have become part of the human self-system. Thus, we can say that in the modern era, an individual's identity is expressed not only through their physical characteristics, but also through their digital footprints.

It can be noted that a social media profile is not just a collection of information, but also an extension of an individual's self-perception and social identity. Therefore, the loss of a digital account or negative social feedback can be evaluated as a negative event from a psychological perspective. Belkin's approach shows that the digital environment is a psychological space where identity is not only expressed, but also formed. However, this is a new direction, the mechanisms of the impact of virtual self-expression on real identity are not yet fully systematized, and additional theoretical and empirical research is needed in this area.

Conclusion. The conclusion from the theoretical-conceptual analysis is that the identity construction and self-boundaries of the digital generation form a complex psychological direction where the risks of internal contradiction intersect with the wide opportunities for self-expression created by the digital environment. The self formed in the virtual space is ensured only when it is integrated with social obligations, adequate self-awareness, and reality in real life.

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Pedagogical Sciences

Developing Primary School Students' Spatial Thinking through Project-Based Learning

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Abstract. Spatial thinking — the capacity to perceive, represent, and reason about the properties, positions, and relationships of objects in space — is a foundational cognitive skill underlying achievement in science, technology, engineering, and mathematics (STEM), as well as everyday problem solving. Despite its documented importance, spatial thinking receives limited systematic attention in primary school curricula, which tend to privilege verbal and numerical reasoning over spatial competence. This paper presents a pedagogical model for cultivating primary school students' spatial thinking through project-based learning (PBL), an instructional approach in which learners engage over an extended period with authentic, open-ended problems that culminate in tangible products or public presentations. Drawing on constructivist and embodied-cognition perspectives, the proposed model embeds three interrelated components of spatial thinking — spatial perception, spatial representation, and spatial reasoning — within sequential project stages: problem framing, spatial investigation, prototype construction, and public presentation. The paper outlines a quasi-experimental pretest–posttest design in which an experimental group receiving PBL-based spatial instruction is compared with a control group receiving conventional instruction across a semester-long intervention with primary school students aged 9–10. Illustrative baseline and outcome data are presented to demonstrate how such a design could be structured, analyzed, and reported, including sample comparative and scoring tables. The discussion considers implications for teacher preparation, curriculum design, and assessment practice in primary education and situates the proposed model within the broader research literature on spatial cognition and project-based pedagogy. The paper concludes that systematically embedding spatially demanding tasks within project-based learning frameworks offers a promising, generalizable avenue for strengthening young learners' spatial thinking, provided that teachers receive adequate preparation and that assessment instruments are validated for the target age group.

Keywords: spatial thinking; project-based learning; primary education; STEM education; spatial reasoning; embodied cognition

Introduction

Spatial thinking is increasingly recognized as a foundational cognitive competence, comparable in importance to literacy and numeracy, yet it remains one of the most neglected strands of primary education (National Research Council, 2006). It comprises the interrelated abilities to perceive spatial properties of objects, to construct and interpret spatial representations such as maps, diagrams, and models, and to reason about spatial relationships in order to solve

problems. A substantial body of cognitive-science research demonstrates that spatial skills predict later achievement and participation in STEM fields, and that these skills are malleable and responsive to targeted instruction and practice (Uttal et al., 2013). Nevertheless, spatial thinking is rarely taught explicitly in primary classrooms; where it appears at all, it is usually confined to isolated units on shapes and geometric vocabulary rather than integrated into sustained, meaningful tasks (Gilligan-Lee, Hawes, & Mix, 2022).

Project-based learning (PBL) offers a promising instructional vehicle for addressing this gap. PBL organizes classroom activity around an extended, authentic project that requires students to investigate a driving question, make design decisions, construct artifacts, and present their reasoning to an audience (Krajcik & Blumenfeld, 2006; Thomas, 2000). Because such projects frequently involve building, measuring, mapping, and modeling, they create recurring, purposeful opportunities for students to perceive, represent, and reason spatially — opportunities that are largely absent from lecture-based or worksheet-based instruction. Prior work applying PBL to spatially rich domains such as geography has shown substantial gains in students' spatial thinking scores (Wei & Zhao, 2026), suggesting that similar benefits might be obtained when PBL is used more broadly across the primary curriculum.

This paper has three aims. First, it reviews the theoretical and empirical literature on spatial thinking and project-based learning in order to establish the rationale for combining them at the primary level. Second, it proposes a structured PBL model, built around a semester-long "Designing Our School Neighborhood Model" project, that explicitly targets spatial perception, representation, and reasoning at each project stage. Third, it outlines a quasi-experimental design — including instruments, procedures, and illustrative data — that could be used to evaluate the model's effectiveness with primary school students aged 9–10. The paper concludes with a discussion of implications for teacher preparation and curriculum design, together with limitations and directions for future research.

Literature Review

The National Research Council's (2006) influential report *Learning to Think Spatially* defines spatial thinking as a constructive amalgam of three elements: concepts of space, tools of representation, and processes of reasoning. Spatial thinking can be supported by simple tools such as pencil and paper or by complex technologies such as geographic information systems, and it can operate at scales ranging from the manipulation of small objects to the navigation of large environments. The report argues that spatial thinking is a generalizable competence that, like literacy, deserves explicit and sustained instructional attention across the K–12 curriculum rather than being confined to a single subject such as geometry or geography.

A key premise underlying interventions such as the one proposed here is that spatial skills are not fixed traits but are responsive to training. In a meta-analysis of 217 training studies, Uttal et al. (2013) reported a moderate average training effect (Hedges's $g = 0.47$) that was stable over time and transferred to untrained spatial tasks, and they argued that spatially enriched education could yield substantial dividends for participation in mathematics, science, and engineering. Classroom-based programs have translated this finding into practice: Burte, Gardony, Hutton, and Taylor (2017) developed Think3d!, an origami- and paper-engineering-based program for elementary students, and found gains in both spatial and mathematical reasoning following the intervention. Reviewing a wide range of such interventions, Zhu et al. (2023) concluded that the relationship between developing students' spatial ability and their capacity to solve spatially complex STEM problems is bidirectional, and they called for spatial activities to be embedded within authentic, discipline-integrated learning experiences rather than taught as decontextualized drills.

Despite this evidence, spatial thinking remains marginal in primary practice, in part because teachers themselves report limited confidence in cultivating it. Gagnier, Holochwost, and Fisher

(2022) surveyed elementary teachers and found that, although teachers generally believed spatial skills to be important for both STEM and non-STEM problem solving, they reported comparatively low self-efficacy for building students' spatial skills during instruction. Gilligan-Lee, Hawes, and Mix (2022) similarly argued that spatial thinking is largely absent from mathematics curricula and called for its explicit inclusion in standards and teacher preparation programs. These findings suggest that any classroom model for developing spatial thinking must be sufficiently structured and well-scaffolded to be usable by teachers who have not received specialized training in spatial cognition.

Project-based learning is defined by several converging features: an authentic, often interdisciplinary driving question; sustained student inquiry and decision-making; collaboration; and a culminating public product (Krajcik & Blumenfeld, 2006; Thomas, 2000). Thomas's (2000) review of the early PBL research literature found consistent evidence that PBL enhances the quality of student learning relative to conventional instruction and is particularly effective for teaching processes such as problem solving and decision making, while also noting that PBL is demanding for teachers to implement well. Bell (2010) further argued that PBL cultivates skills — collaboration, communication, and self-directed inquiry — that are considered essential for success in the twenty-first century. Because PBL projects frequently require students to design, build, and represent physical or conceptual structures, they are a natural vehicle for spatial cognition. This connection has already been demonstrated in geography education: Wei and Zhao (2026) developed a geography PBL model explicitly designed around the components of spatial perception, representation, and reasoning, and reported a substantial increase in students' overall spatial thinking scores following implementation. The present paper extends this logic beyond geography to a general primary-classroom project, arguing that the combination of PBL and explicit spatial scaffolding can be productively applied across subject boundaries.

Taken together, the reviewed literature establishes that (a) spatial thinking is a foundational, trainable competence; (b) explicit classroom interventions can improve it; (c) teachers currently feel under-prepared to teach it; and (d) project-based learning provides a structurally compatible framework for embedding spatial tasks in authentic, sustained classroom work. What remains underdeveloped is a concrete, transferable PBL model — with defined stages, instruments, and evaluation procedures — that classroom teachers outside specialist geography or engineering programs could adopt to build primary students' spatial thinking. The model and illustrative evaluation design proposed in the following section aim to address this gap.

Materials and Methods

A quasi-experimental, pretest–posttest, non-equivalent control-group design is proposed to evaluate the effectiveness of the PBL spatial-thinking model. Two intact fourth-grade classes at the same primary school would be assigned to an experimental condition (PBL-based spatial instruction) and a control condition (conventional instruction using the standard curriculum), respectively. Random assignment of individual students is not feasible in most primary school settings, so intact classes are used as the unit of assignment, with baseline equivalence checked statistically (see Table 1).

The illustrative sample comprises 64 fourth-grade students (aged 9–10) from a primary school, divided into an experimental group ($n = 32$) and a control group ($n = 32$). Table 1 presents baseline demographic and academic characteristics for both groups. Independent-samples *t*-tests and chi-square tests indicate no statistically significant differences between groups at baseline, supporting the assumption of initial equivalence.

Characteristic	Experimental group ($n = 32$)	Control group ($n = 32$)	p-value*
Mean age (years)	9.6 (SD = 0.4)	9.5 (SD = 0.5)	.41

Characteristic	Experimental group (n = 32)	Control group (n = 32)	p-value*
Female / male (n)	16 / 16	17 / 15	.81
Mean prior mathematics grade (0–5 scale)	4.1 (SD = 0.6)	4.0 (SD = 0.6)	.55
Baseline spatial thinking score (0–40)	21.3 (SD = 4.1)	20.9 (SD = 4.3)	.68
Weekly instructional time (minutes)	180	180	—

The experimental group would complete a ten-week project titled "Designing Our School Neighborhood Model," in which students work in small teams to survey a section of their school grounds, represent it at scale, and construct a physical model incorporating proposed improvements (e.g., a garden, a playground feature, or an accessible pathway). The project is organized into four stages, each mapped explicitly onto a component of spatial thinking:

Stage 1 — Problem framing (Weeks 1–2): Teams receive the driving question "How can we redesign part of our schoolyard to make it more useful for everyone?" and begin by discussing what information they would need to answer it, introducing the concepts of scale, perspective, and viewpoint.

Stage 2 — Spatial investigation (Weeks 3–5): Teams measure and sketch the target area, record distances and landmarks, and translate their field notes into a scaled two-dimensional site map, developing spatial perception and representation.

Stage 3 — Prototype construction (Weeks 6–8): Teams build a three-dimensional physical model of their redesigned area from their two-dimensional map, requiring them to reason about how a flat representation corresponds to three-dimensional space (spatial reasoning).

Stage 4 — Public presentation (Weeks 9–10): Teams present their models to classmates, teachers, and, where possible, school administration, explaining and justifying their spatial and design decisions.

The control group covers the same curricular content (measurement, scale, basic geometry) through the school's standard sequence of textbook exercises and teacher-led demonstrations, without the project structure or model-building component.

Spatial Thinking Ability Test (STAT). A 40-item, age-appropriate instrument adapted from established components of spatial thinking assessment (mental rotation, perspective-taking, map reading, and scale reasoning), scored 0–40, administered as a pretest before the intervention and a posttest immediately afterward. Internal consistency and grade-appropriateness would need to be established through piloting prior to use.

Project Product Rubric. A four-criterion analytic rubric (accuracy of scale, clarity of representation, structural coherence of the physical model, and quality of oral justification), each scored 1–4, used to assess the experimental group's project artifacts and presentations.

Teacher Implementation Checklist. A fidelity-of-implementation checklist completed weekly by the classroom teacher to document adherence to the intended project stages.

Both groups would complete the STAT during the same week prior to the start of instruction. The experimental group then undertakes the ten-week PBL project described above, while the control group receives the standard curriculum over the same period and duration of instructional time (Table 1). Both groups complete the STAT again in the week following the intervention. The experimental group's project artifacts and presentations are additionally scored using the Project

Product Rubric by two independent raters, with inter-rater reliability calculated using Cohen's kappa.

Gain scores (posttest minus pretest) on the STAT would be compared between groups using an independent-samples t-test, and within-group pre–post change would be examined using paired-samples t-tests. Effect sizes (Cohen's d) would be calculated for both within- and between-group comparisons. Table 2 presents illustrative descriptive and effect-size statistics consistent with the pattern of results that this design is intended to detect: a substantially larger gain, and a large illustrative effect size, for the experimental group relative to the control group.

Group	Pre-test M (SD)	Post-test M (SD)	Gain score	Effect size (Cohen's d)
Experimental (PBL)	21.3 (4.1)	31.6 (3.8)	+10.3	1.42
Control (conventional)	20.9 (4.3)	24.1 (4.0)	+3.2	0.44

Any implementation of this design would require informed parental consent, child assent appropriate to age, approval from the relevant institutional or school ethics body, and assurances that the control group receives equivalent instructional time and, if the intervention proves effective, subsequent access to the PBL materials.

Conclusion

This paper has proposed a project-based learning model for developing primary school students' spatial thinking and has outlined a quasi-experimental design, including instruments and illustrative comparative data, through which the model's effectiveness could be evaluated. The proposal is grounded in converging evidence that spatial thinking is a malleable, foundational competence (Uttal et al., 2013), that it is currently under-addressed in primary curricula and under-supported in teacher preparation (Gagnier et al., 2022; Gilligan-Lee et al., 2022), and that project-based learning provides a structurally compatible framework for embedding sustained, authentic spatial tasks within ordinary classroom practice (Krajcik & Blumenfeld, 2006; Wei & Zhao, 2026). By explicitly mapping the stages of a classroom project onto the components of spatial perception, representation, and reasoning, the model described here offers teachers a concrete, transferable structure rather than an abstract recommendation to "do more spatial activities."

Should an actual implementation follow the illustrative pattern presented in Section 3, the results would suggest that PBL-based spatial instruction can produce meaningfully larger gains in spatial thinking than conventional instruction over an equivalent period. Such a finding would have practical implications for primary curriculum design, suggesting that spatial competence can be cultivated without introducing a separate subject, provided that existing project or thematic units are deliberately restructured around spatial perception, representation, and reasoning. It would also underscore the need for professional development that gives primary teachers the confidence and pedagogical tools to plan and facilitate spatially rich projects, addressing the low self-efficacy reported in prior research (Gagnier et al., 2022).

Several limitations should be noted. First, and most importantly, the data reported in Section 3 are illustrative rather than empirical; an actual study would need to be conducted, and its results might differ from the pattern presented here. Second, the reliance on intact classes rather than individual random assignment limits causal inference relative to a fully randomized design. Third, a single-school, single-project implementation constrains generalizability across cultural and educational contexts, including trilingual primary settings such as those found in Kazakhstan, where spatial-language and spatial-representation conventions may differ across Kazakh, Russian, and English instructional materials. Future research should therefore replicate the model across multiple schools and grade levels, examine transfer of spatial gains to mathematics and science

achievement, and investigate how project themes and spatial vocabulary might be adapted for multilingual primary classrooms.

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PROJECT-BASED LEARNING IN SLOVAK LANGUAGE EDUCATION FOR PUPILS WITH SPECIAL EDUCATIONAL NEED

Marcela Čarnická

Abstract:

The paper presents the implementation of project-based learning in Slovak language education for pupils with special educational needs, with particular attention to pupils with dyslexia. The intervention focused on consolidating the correct spelling and understanding of selected words through multisensory, movement-based, cooperative and creative activities. Pupils worked with concrete objects, visual supports and word cards and subsequently used selected words in independent creative writing. Differentiated activities were designed to support pupils with dyslexia through visual aids, colour coding, manipulation of objects and structured guidance. The classroom implementation indicated that project-based learning can provide meaningful opportunities for developing language, spelling, cognitive, social and communication skills. Creative and multisensory activities also supported pupils' motivation, active participation and confidence in learning.

Keywords:

Project-based learning; Slovak language education; pupils with special educational needs; dyslexia; selected words

Introduction

Project-based learning represents an educational approach that connects learning with meaningful activities, active participation and the real-life contexts of pupils. For pupils with special educational needs, such an approach may be particularly important because the development of knowledge and competences is closely connected with their opportunities for communication, social participation and future independence. Education should therefore not be understood solely as the acquisition of academic knowledge, but also as part of the development of an individual's life story and their opportunities to participate actively in everyday life and in the wider community (Kováčová & Javorčík, 2025).

One of the main characteristics of project-based learning is that pupils' efforts and the results of their work are presented to the wider community. In our case, the pupils' products were shared beyond the immediate learning environment and became a means of communication with other pupils. This dimension of project-based learning is particularly relevant for pupils with special educational needs, as it provides opportunities to experience their own competence, communicate their ideas and perceive the value of their work for others.

In preparing this form of communication, we were inspired by Freinet's methods. Freinet was an excellent organiser who connected schools into a network in which active correspondence took place. Čapek (2015) describes how schools exchanged packages and letters containing worksheets, local products, descriptions of the local environment and customs. During the implementation of our project, pupils created original texts containing selected words, exercises for practising selected words and educational posters. These materials were subsequently shared with pupils from other classes and schools.

An important element of Freinet education was the printing of pupils' texts using a school printing press. Following this principle, pupils' texts were typed and printed. As Čapek (2015, p. 202) states, "Through printing, pupils' texts acquire an official and definitive character." At the same time, becoming authors of their own texts can help pupils overcome unnecessary respect for the printed word and contribute to the development of critical thinking and reading comprehension. In this sense, pupils' products become more than merely outputs of a lesson: they represent an opportunity for pupils to experience authorship, competence and participation.

Such an approach can be viewed in the broader context of the life story of a person with a disability. Opportunities to express oneself, communicate with others, create meaningful products and experience recognition may contribute to the development of an individual's identity and their perception of themselves as an active participant in social life. Project-based learning can therefore create a space in which educational activities are connected with competencies that extend beyond the classroom and may become meaningful components of an individual's future life trajectory (Kováčová & Javorčík, 2025).

Characteristics of the Slovak Language Subject

"The subject of Slovak language and literature has an irreplaceable position in education. It is a fundamental means of developing pupils' cultural literacy and key competences. It enables pupils to understand and acquire knowledge across all educational areas. For this reason, it occupies a key and central position within the system of primary education" (Učebné osnovy Slovenského jazyka, 2015, p. 1). The competences acquired by pupils through Slovak language instruction have a significant impact on their education in other educational areas and school subjects as well.

"The aim of teaching Slovak at the primary level of education is to teach the standard language to a level that enables pupils to use it in practical life. We understand language use as the comprehensive application of all communication skills – speaking, writing, reading and listening" (Učebné osnovy Slovenského jazyka, 2015, p. 1).

The area of language, speech and communication represents one of the most challenging areas of development for pupils with special educational needs. An important legislative framework for their education is provided by the State Educational Programme for the first stage of primary school in the Slovak Republic and the Educational Programme for pupils with disabilities, whose primary objective is to develop pupils' key competences (Bartoňová, Magová, 2018).

According to Hlebová (2022), the development of competences among pupils with disabilities can be achieved through the fulfilment of the following educational objectives:

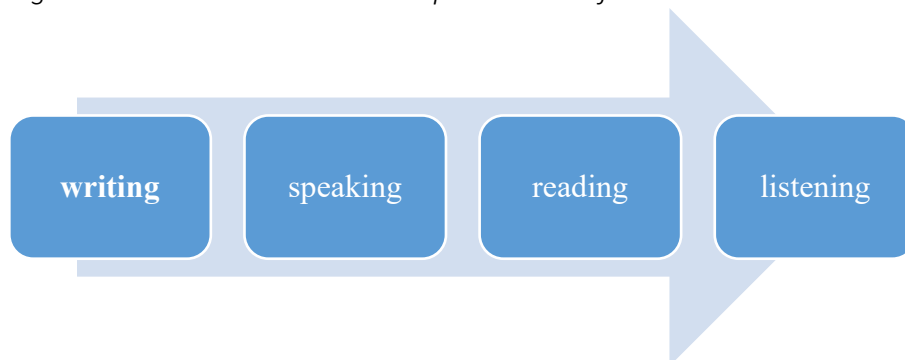
- to develop the pupil's personality comprehensively in the cognitive, social, emotional and moral domains;
- to support pupils' cognitive processes and their competences in critical and creative thinking through their own learning experiences and problem-solving;
- to develop the competences necessary for communication, understanding, evaluation and initiative;
- to support the development of interpersonal and intrapersonal relationships;
- to lead pupils towards tolerance, acceptance, understanding and respect for other people.

"In accordance with the innovation of the educational system based on creative-humanistic education and the comprehensive development of all pupils' personalities within primary education in the context of special and inclusive education, the teaching of the mother tongue and literature should be based on communicative-cognitive, spiral and gradual principles. It should proceed systematically, from the analysis to the synthesis and generalisation of the phenomenon being taught, with a gradual accumulation of new knowledge that should progressively expand, deepen and contribute to the development of pupils' communicative competence" (Hlebová, 2022, p. 13).

When planning mother-tongue instruction, it is important to bear in mind that the knowledge and competences acquired by pupils will also be used in other subjects. Everything pupils learn in Slovak language lessons should therefore be applied across other areas of learning as well. When this occurs, the objectives of language education can be considered to have been fulfilled.

According to the Slovak language curriculum (Učebné osnovy slovenského jazyka, 2015), the specific characteristics of the individual components of the Slovak language and literature subject in the third and fourth grades, when pupils acquire knowledge of selected words, can be formulated as follows (Figure 1).

Figure 1: Individual components of the Slovak language and literature



Source: Slovak language curriculum (2015)

- **Writing** – pupils' ability to write simple texts, particularly descriptions or short narratives, should be developed and utilised. My pupils mainly created short narratives about animals, as most groups of selected words include animal-related vocabulary and this topic was close and familiar to them.
- **Speaking** – it is important to develop pupils' competence to communicate orally in accordance with a particular situation, present their ideas, and use both verbal and non-verbal means of communication. Speaking was extensively used in our project-based learning activities, particularly when presenting results, searching for answers, matching related words and completing other tasks.
- **Reading** – reading is a natural part of the teaching process. My third-grade pupils had already developed relatively well-established reading skills. In our project-based learning, reading helped pupils understand texts written by other pupils and complete various tasks.
- **Listening** – during education, we probably receive the greatest amount of information through hearing. While some pupils in my project-based learning activities developed their presentation skills, others learned to listen effectively.

Writing Texts by Pupils with Dyslexia

One of the components of our project-based learning aimed at consolidating the correct spelling of **selected words (i.e., words in which the spelling of i/y is determined by a grammatical and orthographic rule)** was creative independent writing.

In her book *Mám dyslexiu [I Have Dyslexia]*, Zelinková (2013) proposes several recommendations for writing activities involving pupils with dyslexia:

- **Consider how much information pupils need.** Gathering information can be demanding, as it requires pupils to orient themselves in source materials, which in our case consisted primarily of selected words.
- **Plan the text.** Planning may involve creating an outline or a mind map.
- **Divide the text into smaller parts** and focus on the continuity and logical connections between sentences and ideas.

- **Allow sufficient time for reviewing the written text.** Pupils with dyslexia often fail to notice spelling errors. After reading a text repeatedly, they may also perceive its content less accurately because they have already read it several times. Therefore, it is important to allow sufficient time for revision – for example, by putting the text aside for several days and returning to it later.

Krejčová (2019) also recommends considering the genre and format of the text:

- **Fantasy** – a completely fictional story in which the pupil uses their imagination. This may include, for example, science fiction, a fairy tale or a story set in the past.
- **A story that happened to a particular person** (e.g., someone the pupil knows).
- **A historical event**, a description of a natural disaster, or a description of a discovery or invention.

Krejčová (2019) further recommends establishing the main plot of the story. She also discusses the questions on which pupils should focus. These include, for example: Who are the main characters? What happens? Where does the story take place? When does the story take place? Why does the story take place? Why did it happen? How did it happen?

Prerequisites and Factors Influencing the Acquisition of Selected Words by Pupils with Dyslexia

The first and most important factor in acquiring the correct spelling of selected words is **knowledge and understanding of the words concerned**. Therefore, teachers should provide pupils with dyslexia with a wide variety of exercises and tasks involving selected words so that their correct spelling can gradually become automatised.

According to Klimovič (2024), selected words are organised into individual groups according to:

1. **semantic relatedness** – words that occur less frequently should be explained to pupils;
2. **rhythmic structure** – for example, *býk*, *bylina*, *bystrý*.

The second prerequisite is the ability to **retrieve the sequences of selected words from memory**. Pupils may know entire sequences of selected words by heart but nevertheless make spelling errors when writing them. This occurs quite commonly among pupils with dyslexia. The reason is that the stage at which the pupil retrieves the orthographic form of the selected word and is able to reproduce it correctly in writing has not yet been fully established (Bartoňová, Magová, 2018). According to Baršváryová (2023), the following exercises can be incorporated into spelling practice to support pupils in learning selected words effectively:

- exercises involving the **oral identification of an isolated phenomenon**, including words in forms other than their basic form;
- exercises aimed at **creating word families of semantically related words**, e.g., *bystrý* – *bystrina* – *Bystrica* – *bystrinka*;
- exercises aimed at **reinforcing the correct visual representation of words**, in which pupils construct a selected word from individual letters;
- exercises aimed at **creating strong memory associations** through short sentences;
- exercises involving **searching for names of people, birds, animals, places and objects** from individual groups of selected words;
- exercises using **continuous texts from children's literature rich in selected words**, such as the book *Štúplik a vybrané slová* or *Vybrané slová v obrázkových príbehoch*.

Acquiring a grammatical phenomenon is a complex process that depends on the individual's overall psychological state, the method of instruction, memory, and the ability to retain and retrieve the given grammatical phenomenon. Bednáriková (2021) outlines several factors that may influence the process of learning selected words. Possible factors include:

- **Weakened perceptual abilities** – some pupils may have reduced visual or auditory perception. Reduced visual perception may result in a pupil failing to recognise a word in

a text even though the word has already been learned. A pupil with weaker auditory perception may receive numerous secondary auditory stimuli that interfere with the fixation of the acoustic representation of a word. Some pupils may also have insufficiently developed spatial orientation. All of these factors may affect pupils with dyslexia.

- **Mechanical memorisation without a logical understanding of word meanings** – insufficient explanation of word meanings makes the acquisition of correct spelling more difficult. If pupils with dyslexia are required to memorise sequences of words without understanding their meanings, they may be unable to apply them appropriately in practice.
- **The pupil's psychological and physical prerequisites** – individual differences among pupils in the acquisition of knowledge result from differences in their learning abilities.
- **Reduced reading abilities and limited vocabulary among pupils with dyslexia** – if pupils must continually concentrate on the mechanics of reading, they may fail to notice grammatical phenomena and may have greater difficulty orienting themselves in a text.
- **The family environment** – the family environment and its atmosphere affect pupils in different ways and create different conditions for their learning and schoolwork. Many difficulties may also arise from inconsistent preparation for lessons, which can result in gaps in pupils' knowledge.
- **The teacher and the quality of instruction** – the teacher's didactic competence is important in the educational process. The level of pupils' acquired knowledge depends to a considerable extent on the quality of the teacher's preparation for instruction.
- **Developmental learning disorders** – a considerable number of pupils may also have another developmental disorder, such as dysorthography, dysgraphia or impaired communication ability, which can negatively affect their performance in Slovak language education.

Practical Implementation of Project-Based Learning

The practical part of the project-based learning was implemented through a set of interconnected activities aimed at consolidating the spelling and understanding of selected words among pupils with special educational needs, including pupils with dyslexia. The activities combined movement, manipulation of objects, cooperative learning, creative writing, reading and reflection. The emphasis was placed on active participation, multisensory learning and the gradual transfer of responsibility for learning from the teacher to the pupils.

The introductory activity involved a movement-based game in which pupils collected cards containing selected words. Working in pairs, pupils identified and collected words belonging to a particular group of selected words. For pupils with dyslexia, the cards were visually adapted by using larger print and small illustrative pictures. The movement component was used to support the consolidation of the orthographic form of the words through a kinesthetic learning experience.

Photography 1

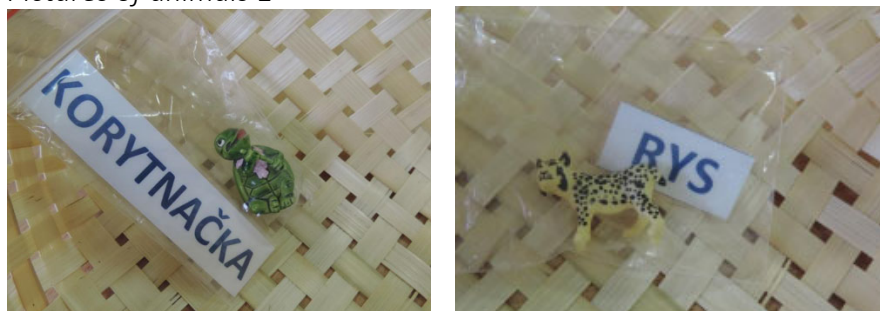


Source: Author's archive

The next activity focused on associating selected words with concrete objects. Pupils worked collaboratively with miniature objects representing particular words and sorted them according to the relevant groups of selected words. The objects were then placed together with the corresponding word cards in labelled containers. This activity combined visual, tactile and motor experiences with repeated reading and verbal reinforcement of the words. It also supported cooperation, communication and social interaction among pupils. For pupils with dyslexia, colour coding was used to distinguish individual groups of selected words and to facilitate their identification.

A central activity of the project was **creative free writing using selected words**. Pupils were asked to create a short narrative on a topic of their choice while using as many selected words as possible. They could work independently or in pairs and could use the objects and word cards as visual and tactile prompts for generating ideas. The teacher provided individual support, particularly by helping pupils structure their ideas into an introduction, main body and conclusion and by using guiding questions to support the development of a coherent storyline. This approach was particularly beneficial for pupils with dyslexia, who were able to produce individual sentences but initially experienced difficulties connecting them into a coherent narrative.

Pictures of animals 1



Source: Author's archive

The written texts were subsequently read, discussed and revised. Pupils were encouraged to present their work to their peers, reflect on their own performance and provide feedback. Selected texts were further transformed into learning materials by omitting selected words, creating exercises that could be used by other pupils. In this way, the pupils' own products became a meaningful part of the learning process and contributed to their sense of competence and the value of their work.

The fixation phase focused on completing a continuous text by inserting appropriate selected words. Pupils physically selected and inserted word cards into corresponding gaps in the text. For pupils with dyslexia, the task was differentiated through colour-coded cards and spaces, together with support in reading the sentences and focusing on the orthographic form of the words.

The activities were concluded with a brief reflection in which pupils evaluated what they had learned, their experience of the lesson, their satisfaction with their work and their perceived success. The implementation demonstrated the potential of project-based learning to combine the development of language and spelling skills with cognitive, social, emotional and motor development. In particular, multisensory activities, movement, visual supports, manipulation of concrete objects and creative writing appeared to provide meaningful learning opportunities for pupils with dyslexia.

Conclusion

The presented classroom-based intervention demonstrates the potential of project-based learning as an effective approach to Slovak language education for pupils with special educational needs. The combination of movement, manipulation of concrete objects, visual support, cooperation and creative writing created opportunities for active and multisensory learning. For pupils with dyslexia, differentiated activities provided additional support in recognising, remembering and correctly using selected words. Creative writing proved particularly valuable as it enabled pupils to apply acquired spelling knowledge in a meaningful communicative context while developing their ability to construct coherent texts. The activities also supported pupils' motivation, cooperation, presentation skills and confidence in their own work. The observed classroom experience suggests that project-based learning can contribute to connecting language learning with cognitive, social, emotional and practical development. Further research should examine the effectiveness of this approach using systematic assessment of pupils' spelling and writing performance before and after the intervention.

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REPRESENTATION OF TRANSPORTATION IN DRAWINGS BY PUPILS WITH INTELLECTUAL DISABILITIES

Barbora Kováčová

Abstract

The paper focuses on the representation of transportation in drawings by pupils with intellectual disabilities. The aim of the research was to analyse the representation of individual categories of transportation-related content in children's drawings and to examine whether differences exist in the way transportation-related reality is represented with regard to pupils' sex. The research sample consisted of 83 pupils with mild intellectual disabilities, aged 11–13 years, attending a special school. Quantitative content analysis was used to process the drawings, with individual motifs categorised into groups of motorised means of transport, other means of transport, and elements of the transportation environment. The results of Pearson's chi-square test and Fisher–Freeman–Halton exact test demonstrated a statistically significant association between pupils' sex and the way transportation was represented. The findings indicate different preferences in the representation of transportation motifs between girls and boys.

Keywords

drawing, pupil with intellectual disabilities, transportation, means of transport, content analysis, artistic expression, sex differences

Introduction

Transportation is closely connected with our everyday lives. It enables us to overcome distances, move people, and transport goods from one place to another. All of this takes place through means of transport, which are an essential part of the functioning of contemporary society, people's lives, and the economy. The development of the infrastructure necessary to ensure transportation is also an important factor in the development and success of a country. From birth, every person naturally encounters various means of transport, which gradually become part of their experiences, perceptions, and everyday life. These experiences may also be reflected in children's play, constructive activities, and artistic expression. Drawing represents a natural means through which a child can express their knowledge, experiences, ideas, and relationship to the surrounding world (Valachová, Rassu Nagy, 2025). The representation of means of transport in children's drawings can therefore provide not only insight into which objects a child knows and prefers, but also into the way in which they visually process their experiences and knowledge. Valachová (2020) argues that, in this context, drawing can be an interesting means of examining the representation of transportation-related themes in children, as well as an opportunity to depict a situation or story that a child visualises (Magová, 2020).

Transportation as a Theme for Expression Through Drawing

Czadró (2008) defines a means of transport as a technical device through the movement of which the transportation of goods or people is carried out. Rybovič (2026) characterises the requirements placed on transportation and means of transport in the contemporary context. These include **speed, readiness, regularity, safety, reliability, smoothness, comfort, adaptability to users' needs, and well-developed infrastructure**. This category primarily includes road motor vehicles, including buses and coaches, as well as trailers, railway vehicles, and vessels used for

passenger transportation. Land transportation is the most widespread form of transportation in the world. It is an integral part of our everyday lives (Czadró, 2008). We use transportation to travel to work, schools, and shops. It is part of the modern lifestyle and enables us to travel easily between cities, countries, and regions. Every person has individual transportation options depending on the region or country in which they live. In our country, as elsewhere in the world, there are regions where railway transportation is unavailable or where motorways and expressways are absent. People must therefore seek transportation options based on the efficiency, affordability, and convenience of travel. The most common representative of land transportation is the automobile. Cromer (2025) defines an automobile as a motorised road vehicle designed to transport people or goods, characterised by its own propulsion, most commonly provided by an internal combustion engine, an electric motor, or a combination of the two, thereby providing a high degree of mobility and independence in transportation.

Specific Features of Drawing in Individuals with Intellectual Disabilities

Vágnerová (2017) explains that intellectual disability, including a reduction in intellectual abilities below the average level, manifests itself in all areas that depend on cognitive functioning, including drawing. Children with lower intellectual abilities or intellectual disabilities can be expected to demonstrate a lower quality of drawing performance compared with their typically developing peers, while the crucial factor is the particular aspect of drawing in which the deficit is most pronounced. Drawing performance is influenced not only by the severity of the disability but also by its cause, which may be associated with additional difficulties such as attention disorders, impulsivity, or impaired fine motor skills. The co-occurrence of multiple disabilities generally results in a more pronounced reduction in the quality of drawing.

Valenta and Müller (2021) state that the drawings of children with intellectual disabilities lag behind the typical developmental norm in many respects, although this lag is individual and uneven and depends on the degree of disability. This, however, represents only a general outline of the issue and does not take into account other important factors, such as the cause of the disability. Etiology plays an important role, as the quality of artistic expression may vary according to the type of disability. For example, children with Down syndrome have been found to demonstrate weaker drawing performance compared with children whose intellectual disability has other causes. Kováčová (2023) points out that drawings by children with intellectual disabilities tend to be poor in detail, and the size of the depicted object often does not correspond to the size of the area available on the paper. The colours used by children are often influenced by spontaneity, personal emotions, and the author's preferred colours. Drawings by children with intellectual disabilities may reflect a certain degree of confusion and unclear ideas, resulting in an overall lack of coherence in the representation. In addition, the drawing is often compressed toward the lower edge of the paper. Vágnerová (2017) raises the important question of whether the drawing development of children with intellectual disabilities follows the same pattern as that of typically developing peers but at a slower pace, or whether it also differs qualitatively. Research indicates that the drawings of children with intellectual disabilities correspond to the level of drawings produced by children of the same mental age who are chronologically younger.

The development of drawing skills in individuals with mild intellectual disabilities is not fundamentally different; however, it is significantly slower, and the level of development tends to stagnate at an earlier stage. Drawing expression is closely related to the level of intellectual functioning: the greater the impairment of cognitive functions, the more pronounced its impact on the quality of drawing. This is manifested particularly in simplified representations, a higher number of inaccuracies, and a lower level of detail.

Drawing itself and its means of expression can also become a creative activity (Čarnická, 2024), through which individuals with intellectual disabilities may learn to depict details that may be

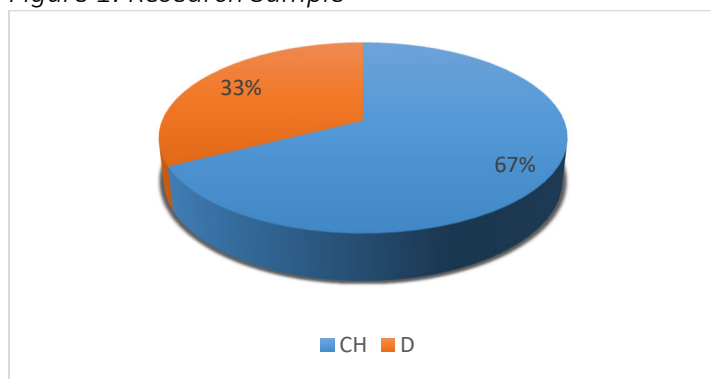
absent from their spontaneous drawings. This aspect should also form part of the strategies employed by inclusive teachers, regardless of the particular group of children or pupils with whom they work (Rassu Nagy, 2024; Muratkyzy & Bolatovna, 2026; Bakhytzhankyzy & Bolatovna, 2026).

Research Design

The study analysed the content of children's drawings, focusing on the representation of transportation-related themes. The analysis examined the selection and representation of individual means of transport, as well as other elements associated with the transportation environment. The research sample consisted of **83 pupils with intellectual disabilities aged 11–13 years**, whose drawings focused on the theme of means of transport. All pupils attended a special school for pupils with intellectual disabilities or multiple disabilities.

The research sample consisted of pupils aged 11–13 years with **mild intellectual disabilities**. The sample was heterogeneous in terms of sex, comprising 27 girls (33%) and 56 boys (67%).

Figure 1: Research Sample



Each pupil with intellectual disabilities in the research sample was represented by **one drawing and one dominant type of means of transport** (Table 1).

Table 1: Means of Transport Represented

	Girls	Boys	Σ
Car	8	21	29
Bus	2	11	13
Tractor	1	7	8
Scooter	2	2	4
Airplane	2	2	4
Bicycle	1	2	3
Elements of the traffic environment (traffic lights, roads, traffic signs)	6	3	9
Boat	0	2	2
Train	5	6	11
	27	56	83

A **quantitative content analysis** was used to evaluate the drawings, enabling the systematic identification of the frequency of occurrence of individual content categories in children's visual artistic expressions. Each drawing was classified according to the dominant depicted motif into one of the predefined categories. The analysis of drawings created by pupils with intellectual disabilities was understood as an analysis of the visual content of children's artistic expression.

The results were not interpreted as direct indicators of children's psychological characteristics, but rather as characteristics of the ways in which the selected topic was represented.

The basic categorization included individual types of means of transport: **bus, tractor, train, bicycle, scooter, airplane, boat**, and **elements of the traffic environment** (e.g., road, traffic lights, traffic signs).

Due to the low frequency of some individual categories of means of transport, the original categories were grouped according to their content similarity. This grouping made it possible to preserve the semantic character of children's drawings while creating categories suitable for subsequent statistical analysis. The grouping process was based not only on statistical requirements but also on the content interpretation of the drawings. Another argument for this approach was that the analysis did not focus solely on "**which vehicle the child drew,**" but rather on **how the child thematically processed the content related to transport**. Therefore, the creation of broader content categories was considered methodologically justified. The resulting categories represented different ways of depicting transport reality:

- motorized means of transport,
- other means of transport,
- elements of the traffic environment.

Table 2: Categorization of transport-related content in children's drawings

Category of transport-related content	Girls	Boys	Σ
Motorized means of transport (car, bus, tractor)	11	39	50
Other means of transport (train, bicycle, scooter, airplane, boat)	10	14	24
Elements of the traffic environment (road, traffic lights, traffic signs)	6	3	9
Total	27	56	83

To verify differences in the distribution of individual categories according to gender, the Pearson chi-square test of independence was applied. Statistical significance was assessed at the significance level of $\alpha = 0.05$. The result was $\chi^2(2) = 8.217$; $p = 0.016$. Since $p < 0.05$, the null hypothesis was rejected.

A statistically significant association was found between pupils' gender and the representation of transport-related themes in their drawings. Girls and boys differed statistically significantly in the type of transport content depicted in their drawings.

Table 3: Effect size of the association between gender and transport-related content representation

Effect size measure	Result	Interpretation
Cramer's V	$V=0,315$	• $V \approx 0.10 \rightarrow$ small effect • $V \approx 0.30 \rightarrow$ medium effect • $V \approx 0.50 \rightarrow$ large effect

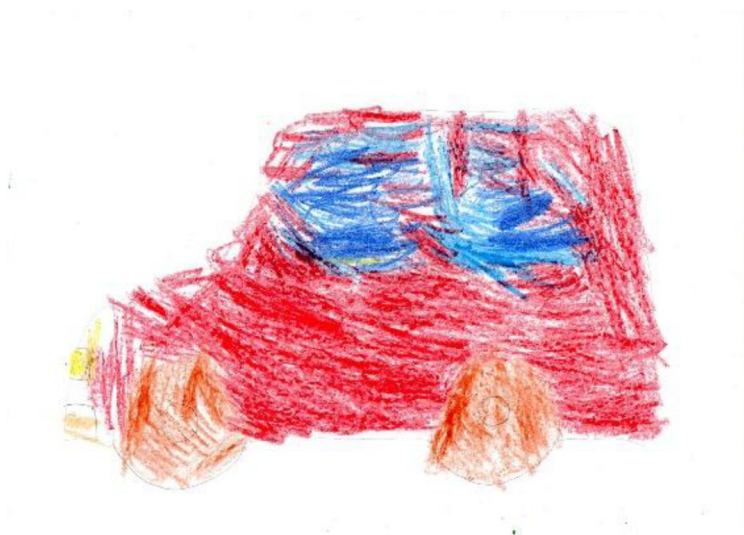
The results of the chi-square test demonstrated a statistically significant association between children's gender and the choice of transport means depicted in their drawings ($\chi^2(2) = 8.217$; $p = 0.016$). The value of Cramer's $V = 0.31$ indicates a medium strength of association between the examined variables. The result therefore demonstrates a **medium practical effect**.

Presentation of Transport-Themed Drawings

Selected examples of depicted means of transport are presented for illustrative purposes, accompanied by a brief analysis of the represented objects.

The drawing represents a passenger car depicted from a side view. The child captured the basic characteristics of the vehicle, including the body, wheels, and windows. The dominant color is red, while the windows of the vehicle are highlighted in blue. The drawing focuses exclusively on the transport object itself, without depicting the wider traffic environment, and was classified within the category of **motorized means of transport**.

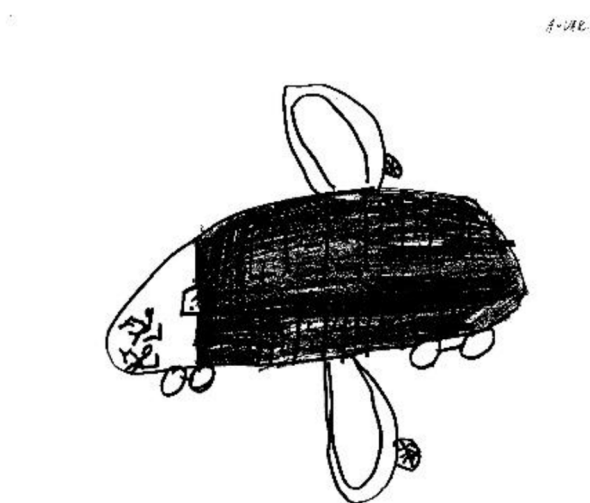
Figure 1. Car drawn by an 11-year-old boy with intellectual disability



Source: Author's archive disability

The drawing depicts an airplane from a top-view perspective. The child represented the basic structural features of the aircraft, including the fuselage and wings. The dominant expressive element is the pronounced use of color to highlight the fuselage. Despite the schematic style of representation, the depicted means of transport is clearly identifiable (Figure 2).

Figure 2. Airplane drawn by a 12-year-old pupil with intellectual Source:



Source: Author's archive disability

From a developmental perspective, the drawing indicates the child's ability to identify and thematically group objects according to their shared meaning, a form of representation that may be more challenging to achieve in drawings created by some individuals with intellectual disabilities.

The child does not focus solely on isolated means of transport but creates a simple situational context – traffic on a road. The repeated use of lines on the road may be associated with an attempt to emphasize the surface structure or the dynamics of movement within the scene (Figure 3)

Figure 3. Cars drawn by an 11-year-old boy with intellectual disability

Source: Author's archive disability



Summary of Research Findings

Differences in the representation of transport-related themes according to gender were examined using the **Pearson chi-square test of independence**. The results demonstrated a statistically significant association between children's gender and the category of depicted transport content, $\chi^2(2) = 8.217$; $p = 0.016$. The effect size expressed by **Cramer's V coefficient** reached a value of 0.315, indicating a moderate strength of association. Boys depicted motorized means of transport more frequently (69.6%), whereas girls more often represented elements of the traffic environment (22.2% compared to 5.4% among boys).

Due to the low frequencies in some categories, the relationship between the variables was additionally verified using the **Fisher–Freeman–Halton exact test**. The results confirmed a statistically significant association between children's gender and the way transport-related themes were represented in their drawings ($p = 0.015$). Boys more frequently depicted motorized means of transport, while girls relatively more often represented elements of the traffic environment. The statistically significant result remained unchanged even after applying the more conservative exact test ($\chi^2 p = 0.016$; Fisher $p = 0.015$).

Conclusion

The analysis of drawings created by pupils with intellectual disabilities revealed the diversity of ways in which children represent transport-related themes in their visual artistic expression. The most frequently depicted category consisted of motorized means of transport, with cars occupying the dominant position. Statistical analyses demonstrated a significant association between pupils' gender and the way transport-related content was processed in their drawings. Boys more frequently represented motorized means of transport, whereas girls more often depicted elements of the traffic environment.

According to the value of Cramer's V, the identified association showed a moderate strength, indicating the practical relevance of differences between the observed groups. The application of exact testing further confirmed the stability of the obtained results while taking into account the low frequencies within individual categories. Drawing therefore appears to be an appropriate tool for capturing the ways in which pupils with intellectual disabilities process and interpret knowledge from their everyday environment. The findings may be utilized in the planning of educational activities aimed at developing the cognitive, communicative, and expressive abilities of these pupils.

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ცვალეზადი საერთაშორისო უსაფრთხოების სისტემა და კიბერუსაფრთხოება

Changing International Security Systems and Cybersecurity

თამთა კოდუა

Tamta Kodua

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Abstract

In the contemporary era, it is inconceivable to sustain any form of interaction without digital technologies. Consequently, cyber threats have emerged as a new global challenge, significantly impacting international security. The growing scale and complexity of risks originating from cyberspace further underscore the urgency and relevance of this issue.

Cyber and information security constitute a major concern worldwide, representing a novel challenge for states and exerting substantial influence on the international security environment. As a result, leading global actors face increasing difficulties in addressing cybersecurity threats. In this context, cybersecurity has acquired critical importance in the geopolitical modeling of the 21st century, particularly in ensuring global security.

The article discusses the key characteristics and specific features of cybersecurity. It also addresses issues such as the role of international and regional organizations in ensuring cybersecurity and identifies the capabilities of leading states in cyberspace in this direction. Furthermore, the paper analyzes how the non-proliferation regime of weapons of mass destruction influences the current international security environment, including its cyber dimension. In addition, it explores the role of cybersecurity in the geopolitical modeling of strategic competition in the 21st century.

The novelty of the study is: determining the impact of cybersecurity on the international security system under conditions of a changing world order. The research provides an in-depth examination and detailed analysis of the approaches adopted by regional and global actors, as well as the key factors shaping cybersecurity policy, drawing on examples from leading states. Furthermore, the paper explores the role of international and regional organizations in ensuring cybersecurity and assesses the capabilities of leading states in cyberspace in this direction. It also analyzes the role of cybersecurity in the geopolitical modeling of strategic competition in the 21st century.

Introduction

Over four decades, the geopolitical map of the Cold War underwent significant transformation, which can be divided into three main stages: 1) 1945–1956: the formation of a security zone - namely, the so-called “*cordon sanitaire*” - around the Soviet Union; 2) 1957–1979: the penetration of Communism into the Western geopolitical space; 3) 1980–1989: the withdrawal of the Soviet Union from maritime dominance and the emergence of a third pole of geopolitical power.

During the first phase of the Cold War, the geopolitical spaces in which the Soviet Union and the United States exercised their hegemonic power - namely, the continental area of Eurasia and the maritime domain, respectively - were clearly delineated, according to the geopolitical terminology of Saul Bernard Cohen (2003). The integration of Central and Eastern European

Communist states into the Warsaw Pact strengthened the continental sphere of Soviet influence. Against the backdrop of fears of Communist expansion, the United States, under Harry S. Truman, initiated a “cordon sanitaire” policy in Europe through the establishment of NATO, alongside the creation of CENTO in the Middle East and Central Asia, SEATO in Southeast Asia and bilateral security agreements with Japan in the Far East. Geopolitical transformations primarily occurred in the boundary regions between the Soviet security zone and the Western “cordon sanitaire.” The evolution and outcomes of the Indochina War, the Chinese Civil War and the Korean War were instrumental in shaping these territorial adjustments. By the mid-1950s, these developments contributed to the stabilization of the dividing lines between the two principal geopolitical spheres.¹

Following the Soviet Union’s attainment of ballistic nuclear parity in 1958, its foreign policy became more ideologically flexible. This shift toward a self-proclaimed liberation mission against colonial imperialism enabled the Eastern Bloc to penetrate the United States’ maritime sphere of influence on a global scale. With enhanced naval capabilities, the Soviet Union expanded its influence primarily in the Middle East, the Horn of Africa, Southeast Asia and the Caribbean basin. This expansion was facilitated by the decline of European colonial power, the growing appeal of socialist postulates among liberation movements and the emergence of the Non-Aligned Movement. The extension of Soviet power contributed to instability in the regions it penetrated, transforming them into what Saul Bernard Cohen (2003) characterizes as “shatterbelts” or zones of conflict.²

In contrast to the traditional conception of these geographical spaces and the “Third World” more broadly - as the Cold War “periphery” and merely passive recipients of superpower policies, the recent large-scale integration of countries and regions of the “Global South” into Cold War studies has shed light on significant, decentralized perspectives vis-à-vis the “Global North.” This shift has revealed the presence of autonomous and active state actors, as well as South–South interactions, thereby challenging the perception of superpowers as omnipotent and exclusive centers of attraction. The historiography of Latin America, long regarded as the geopolitical “backyard” of the United States (Klaus Dodds, 2003, p. 210); and a region that was particularly affected, both rapidly and intensely, by Washington’s responses to Soviet (and broader leftist) influences, reveals a complex network of relationships between Latin America and the wider Global South.

Even before the end of the Cold War, during the 1980s, the economic decline of the Soviet Union forcing its gradual withdrawal from the global stage, contributed to the emergence of East Asia as a new, third geostrategic space. Japan’s economic strength, together with the consolidation of Taiwan, Hong Kong, South Korea and Singapore as economically significant actors, the exponential growth of China and the establishment of robust trade and economic linkages among them, transformed the region into a new and influential element of the global geopolitical balance.

Main Body

Although the Allies reached agreements during negotiations in Tehran, Yalta and San Francisco on the principles and governing structures of the new international system, the coexistence of two incompatible international orders from 1945 onward rendered the full functioning of such a system impossible. The guiding principle of international cooperation, which was intended to be embodied by the United Nations, was not fully upheld by the system’s hegemonic members. The absence of coercive enforcement mechanisms - deliberately not

¹ BRZEZINSKI, Zbigniew. *The Cold War and Its Aftermath*. *Foreign Affairs*, v. 71, n. 4, p. 31-49, Fall 1992.

² COHEN, Saul Bernard. *Geopolitics of the World System*. Lanham: Rowman & Littlefield, 2003.

granted to the United Nations by its founders - resulted in its reversion, within Neorealism conceptualized by Kenneth Waltz (1979), to an anarchic systemic configuration dominated by two superpowers and characterized by rivalry between them. Through a combination of these systemic elements, this rivalry produced a balance of power that ensured a relative degree of stability within the international system.

The defining characteristic of the system was its bipolar nature, in which two blocs functioned as “full-fledged security communities,” each with its own principles, structures and institutions - composed exclusively of their respective members, while not contradicting the general principles embedded in the Charter of the United Nations. Henry Kissinger identifies two distinct sets of balances “that, for the first time in history, were independent of each other: the nuclear balance between the Soviet Union and the United States and the internal balance within the Atlantic Alliance, which was in important respects psychological in nature.” It was precisely bipolarity, together with this mutual independence, that conferred a certain degree of stability on the system. In his influential 1986 article, which remains relevant today, John Lewis Gaddis emphasizes that a simple bipolar structure was less prone to instability than a multi-polar system and did not require continuous adjustment by particularly skilled leadership. Stability was further reinforced by the realist character of the Cold War international system, as it accurately reflected the distribution of power that emerged in the aftermath of the Second World War. In addition, the geographical separation of the two superpowers, combined with the limited economic and social interdependence between them, contributed, according to the author, to the stability of their relationship.

Beyond these structural arguments, Gaddis’s (1986) analysis also advances other strong explanations regarding the behaviour of the core actors, which functioned as catalysts of systemic stability: their low propensity toward direct military confrontation, or, in other words, a calculated risk-taking policy grounded in nuclear deterrence and mutually assured destruction. Ideological moderation throughout the conflict also contributed to stability. Both poles adapted their universalist ideological discourses to conform to the basic principles of the status quo, namely the coexistence of two international orders within their respective spheres of influence. As a result, an implicit pattern of norms emerged, functioning as mutually accepted rules of the game: respect for spheres of influence, a veto on direct military confrontation, the use of nuclear weapons only as a last resort, and a preference for preserving anomalies rather than forcing changes that could lead to unpredictable outcomes - examples include Fidel Castro’s Cuba and the Berlin enclave. Within this framework of rules, systemic bipolarity became more flexible due to the possibility of moderate intra-bloc disagreements within certain limits, such as European autonomy under the leadership of Charles de Gaulle and Willy Brandt’s Ostpolitik, or the distinctive course of Nicolae Ceaușescu’s Romania, and the dissident stance of Mao Zedong’s China, which contributed to the Sino-Soviet split and marked a shift toward multipolar tendencies in the 1960s and 1970s, while remaining compatible with the system’s fundamental bipolarity. Similarly, smaller actors in the system often pursued what they could obtain from the two hegemonic superpowers, either by balancing between blocs - such as Nehru’s India or Nasser’s Egypt - or by leveraging alignment benefits, as in Castro’s Cuba or Sukarno and Suharto’s Indonesia.³

Despite tensions, crises and proxy wars, the Cold War international system was also characterized by what has been described as a “remarkable history of negotiation and institution-building through the Iron Curtain.” Initiatives such as the Baruch Plan, Atoms for Peace and the Open Skies proposal during the early phase of the Cold War were linked to the interests of Washington DC and Moscow in achieving global agreements. A significant series of arms control treaties, including the Treaty on the Non-Proliferation of Nuclear Weapons, along with

³ GADDIS, John L.. *We Now Know: Rethinking Cold War History*. Oxford: Clarendon Press, 1997.

agreements related to decolonization processes, the establishment of development assistance structures and policies within the framework of the United Nations, and the creation of new agencies and resolutions, as well as, notably, the Helsinki Accords, collectively demonstrate the international system's limited yet real capacity to manage the evolution of the international community and address fundamental global challenges.

It is precisely the evolution of the international system that cautions against any static conception of the Cold War. Many authors have identified a cyclical pattern of development beneath an apparent continuity, characterized by periods of heightened tension followed by phases of *détente*, which often culminated in mutual understandings or agreements. These were subsequently succeeded by renewed escalation, leading to proxy wars or severe diplomatic confrontations. Within this framework, the conceptualization of *détente* phases is of particular importance, and various chronologies have been proposed. A “mini-*détente*” can be identified in 1963, following the Cuban Missile Crisis of the previous year and a more substantial and prolonged *détente* is often associated with the period between this point and 1975. Odd Arne Westad (2007, pp. 194–206) defines the *détente* phase as spanning the period from 1968 to 1975 in superpower relations, whereas Fred Halliday (1983) extends it from 1969 to 1979, positioning it as an intermediate phase between the first Cold War (1946–1953) and the phase of shifting balance of power (1953–1969) and what he terms the “Second Cold War” (from 1979 onward). Given this diversity of interpretations, Bruno Manhou and Roulleau and Royo (2014) convincingly argue that there was not a single *détente*, but rather multiple *détente* phases, each with distinct justifications and characteristics.⁴

Cybersecurity encompasses boundless challenges, while response mechanisms largely remain confined to the national level, which in itself is insufficient. Significant gaps persist both in the understanding of the issue and in the technical and governance capacities required to address it. Moreover, issues of democratic governance—particularly those related to control, oversight, and transparency—have been largely absent from the debate. These challenges are further exacerbated by the substantial role played by private actors, both individually and in cooperation with governments, in all forms of online security. Given the pace at which states and private companies are strengthening cyber defenses and preparing for cyber warfare, the need to address problems of democratic governance has never been more urgent. These issues are the main topic of the presented study.

States, of course, are particularly concerned with national security and the possibility that state or non-state actors, or organized groups, may steal, alter, destroy, or otherwise disrupt critical information and information infrastructure. A major national security concern relates to the risk of disruption to telecommunications, electricity grids, energy pipelines, refineries, financial networks, healthcare systems and other essential services. The case of Estonia (see annex 3) demonstrates that such concerns are far from unfounded and many have gone so far as to argue that cyber warfare, as this type of threat is broadly termed, will transform warfare as dramatically as the introduction of other major technologies has done in the past. Indeed, it can be argued that cyber warfare represents a second wave of revolution in military affairs and displaces kinetic force as the principal agent of war. It raises fundamental questions regarding what constitutes critical infrastructure, what constitutes an attack and what role the security sector can or should play in defense or counteroffensive operations. As will be discussed below, cyber warfare has blurred the categories of both targets and attackers (both civilian and military). Accordingly, serious questions arise as to what forms of credible and legitimate response states can employ in the event of large-scale cyber warfare - whether diplomatic demarches, formal protests, economic measures, criminal prosecution, or military strikes.

⁴ HALLIDAY, Fred. *The Making of the Second Cold War*. London: Verso, 1983.

Conclusion

Cybersecurity creates a triple challenge. There is a dual (at times additional) set of challenges related to both public and private security in ensuring the protection of IT networks and in countering criminal and violent groups that exploit them to achieve their objectives. These challenges require the establishment of comprehensive mechanisms of public–private cooperation. At the same time, cybersecurity represents a growing challenge for democratic governance, as public and private efforts to secure IT networks and monitor the traffic they carry must be balanced against human security concerns and, in particular, human rights such as privacy and freedoms of expression and association. Accordingly, the subsequent discussion is divided into two main parts. The first part provides a brief overview of the main threats and relevant actors, with particular emphasis on public–private cooperation. The second part addresses the key issue of democratic governance and is further divided into subsections concerning oversight, the protection of human rights and finally potential democratic governance challenges related to cyber warfare.

Threats - One of the distinctive features of cybersecurity is that it is often extremely difficult, if not impossible, to accurately identify the perpetrators of an attack or, in many cases, its country of origin. Thus, it is relatively easy for individuals or groups of malicious actors to conceal their involvement or impersonate other users. We will return to this issue below, but setting aside questions of attribution, the following two tables illustrate, in general, the main sources and targets of online threats.

Actors - One of the key challenges of cybersecurity and an aspect that generated particular interest within the Horizon 2015 project, is the fact that although governments generally bear certain responsibilities for information and communication networks, such networks are predominantly owned and operated by private actors. In recent years, several relevant international instruments have been adopted, including United Nations General Assembly resolutions UN General Assembly Resolution 55/63 of 4 December 2000 and UN General Assembly Resolution 56/121 of 19 December 2001, both concerning the fight against the criminal misuse of information technologies. At the global level, the “Guidelines for Cooperation between Law Enforcement Agencies and Internet Service Providers against Cybercrime,” adopted at the Global Conference “Cooperation against Cybercrime” held in Strasbourg on 1–2 April 2008, further emphasize the importance of public–private cooperation. At the regional level, the Council of Europe Recommendation Council of Europe Recommendation No. R (89) 9 and the broader framework of the Council of Europe Convention on Cybercrime require member states to adopt legislative measures establishing investigative powers and procedures for criminal activities committed through computer systems, as well as for the collection of electronic evidence.

It is also highly relevant to consider international and regional human rights instruments, including the International Covenant on Civil and Political Rights (namely, Article 17 on the right to privacy, Article 19 on freedom of expression and Article 22 on freedom of association), the European Convention on Human Rights, the African Charter on Human and Peoples’ Rights, and the American Convention on Human Rights. International and regional organizations have also sought to address electronic data protection more specifically through various measures and instruments, such as the United Nations General Assembly guidelines on the regulation of computerized personal data and the Council of Europe Convention for the Protection of Individuals with regard to Automatic Processing of Personal Data. In particular, these instruments reiterate safeguards related to the confidentiality of electronic data and communications, as well as the protection of privacy and freedom of expression. Society represents another crucial element and there is a clear need for its inclusion through educational campaigns aimed at raising

awareness of fraud, personal data theft, kidnapping risks, ethical considerations and the protection of corresponding rights.⁵

When states act in isolation in the face of both traditional and non-traditional security challenges, they are generally poorly equipped to respond effectively. Consequently, the establishment of security governance networks and in particular public–private partnerships, is becoming increasingly essential. Cybersecurity represents another highly relevant illustration of this problematic. A range of factors further intensifies the oversight challenges generated by cybersecurity and the associated both public and private cooperation.

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Architecture

FORMATION OF THE ARCHITECTURAL IDENTITY OF THE CITY OF AKTAU UNDER ARID CLIMATIC CONDITIONS

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Abstract. *This paper analyzes the architectural and urban planning solutions employed in the design of the city of Aktau (known as Shevchenko in 1964–1991) within the desert environment of the Mangystau Peninsula. It examines the influence of limited green infrastructure, intense solar radiation, dust-laden winds, and extreme temperature fluctuations on the planning of residential districts, the pattern of urban development, and the organization of public spaces. The study identifies the role of climatic factors in shaping the city's distinctive architectural identity.*

The formation of an urban environment under extreme climatic conditions represents one of the most complex and relevant challenges in architectural and urban planning research. A remarkable example of a comprehensive solution to this challenge in the twentieth century was the construction of the city of Shevchenko (now Aktau) on the eastern coast of the Caspian Sea. Built under severe arid climatic conditions characterized by freshwater scarcity, strong winds, intense solar radiation, and saline soils, the city became both a scientific and an urban planning experiment aimed at creating a comfortable living environment in a desert landscape. The aim of this study is to comprehensively analyze the formation of the architectural identity of the city of Shevchenko under arid climatic conditions, to identify the principal urban planning and architectural principles that shaped its spatial organization and climatic adaptation, and to assess their relevance for contemporary architectural and urban design practice in arid regions. The study employs a set of complementary research methods. The historical-chronological method was used to identify the main stages in the formation and development of Shevchenko's architecture and to trace changes in its urban structure and architectural identity. The comparative-typological method enabled a comparison of the city's residential, public, and administrative buildings, revealing both common and distinctive characteristics of their planning, structural, and compositional solutions. The architectural-artistic method was applied to examine the compositional organization of the urban fabric, the plastic treatment of façades, the use of solar-shading devices (brise-soleil, loggias, and balconies), and decorative elements in the context of the formation of a coherent image of Soviet modernist architecture. The constructive-tectonic method was employed to investigate construction technologies, evaluate the use of locally available shell limestone, and assess the durability of structural systems under aggressive natural and climatic conditions. In addition, an analysis of archival documents and published literature was conducted to synthesize previous scientific and design studies, examine planning documentation and graphic materials, and review the relevant historical and regulatory framework.

The planning and construction of Shevchenko on the Mangyshlak Peninsula built upon the experience gained from developing new cities in the arid regions of the USSR, particularly the city of Navoi. Although only a short period separated the establishment of these cities, Shevchenko represented the next stage in the evolution of Soviet urban planning. Its master plan was developed in 1964 by architects who had previously worked on Navoi, ensuring continuity while adapting planning principles to the peninsula's distinctive environmental conditions [1].

Before large-scale development, Mangyshlak remained a sparsely populated territory characterized by severe climatic conditions, including freshwater scarcity, saline soils, extreme summer temperatures, strong winds, and frequent dust storms. The city was named after Taras Hryhorovych Shevchenko, who had spent part of his exile in this region [3]. Although the peninsula's natural resources had been identified as early as the late nineteenth century, systematic geological exploration and industrial exploitation began only after major oil and gas reserves had been confirmed.

Industrial expansion was accompanied by rapid infrastructure development. Railways connected Mangyshlak with the Ural region, Siberia, and Central Asia, while the seaport of Aktau established maritime links across the Caspian Sea. The commissioning of the Uzen–Guryev–Volga oil pipeline in 1970 integrated the region into the Soviet oil transportation network, transforming Mangyshlak into an important industrial center within a relatively short period [2].

The construction of Shevchenko involved numerous technical, economic, and architectural challenges. Saline soils and highly mineralized groundwater accelerated the corrosion of steel and reinforced concrete structures, making anti-corrosion protection an essential requirement. At the same time, the absence of transport infrastructure and local construction materials complicated the delivery of equipment and building supplies. Freshwater scarcity represented one of the greatest challenges. To address this problem, an autonomous nuclear-powered energy and desalination complex was constructed, enabling the city to rely almost entirely on desalinated seawater for domestic and industrial needs [3].

The planners sought not only to accommodate industrial facilities and housing but also to create a comfortable and attractive urban environment capable of supporting permanent settlement. During the city's early development, extensive public infrastructure was established, including preschools, schools, healthcare facilities, cultural institutions, sports complexes, and commercial services [3].

The planning concept was based on the functional separation of industrial, residential, and municipal service zones connected by efficient transport and engineering infrastructure [4]. The elongated coastline determined the city's linear spatial structure, with functional zones arranged parallel to the Caspian Sea. Recreational areas occupied the waterfront, residential districts were located on elevated terrain behind them, and municipal service areas were placed further inland, separated by wide green protective belts.

Residential districts were connected by longitudinal transport routes, while landscaped transverse boulevards linked neighborhoods with the waterfront. These green corridors improved pedestrian accessibility, promoted natural ventilation by channeling cool sea breezes into the urban fabric, and created spatial separation between residential blocks. This planning approach enhanced environmental comfort while allowing for the city's gradual expansion [1].

The architectural identity of Shevchenko was strongly influenced by its coastal landscape and by the extensive use of locally available shell limestone. Although this material had relatively low strength, it was economical, easy to process, and visually expressive, making it the principal wall material during the initial construction stage [3].

Between 1961 and 1964, architects developed residential and public buildings adapted to the hot desert climate. Gallery apartment buildings became one of the city's most distinctive housing types. Their dual-oriented apartments provided effective cross-ventilation, while open

galleries were generally located on the northern façade and living spaces opened onto spacious loggias that served both as outdoor living areas and as protection from intense solar radiation. These buildings contributed significantly to the city's architectural character and reflected climate-responsive design principles [4].

Although gallery housing exposed circulation spaces to dust, heat, and winter winds, it also increased construction efficiency by allowing more apartments to be served by a single circulation core [3]. Typical apartments featured spacious loggias, built-in furniture, and layouts adapted to local climatic conditions. Improvements in the quality of local shell limestone later enabled the construction of five-story residential buildings instead of the earlier three- and four-story structures [4].

The introduction of prefabricated reinforced concrete components, including floor slabs, ventilation units, solar-shading devices, staircases, and façade elements, significantly improved construction efficiency and stimulated the development of the local building industry. As production capacity expanded, construction gradually shifted toward large-block technology using concrete made with crushed local shell limestone aggregate. This innovation enabled the construction of seven- to nine-story residential buildings, increasing urban density, reducing infrastructure costs, and creating a more expressive city skyline.

An important feature of Shevchenko's residential development was the construction of eleven-story corridor-type apartment buildings containing 120 apartments. Their distinctive plan resembled an open book, with two wings connected at an angle of 120°. These buildings were intended primarily for single residents and small families.

Large-panel housing construction was introduced after the establishment of a local prefabrication plant and the adaptation of the standard Series 1-464-A designs to the climatic conditions of Mangyshlak. A specialized series, 1-464-UM, was developed specifically for Shevchenko. It included apartments ranging from one to five rooms, enlarged kitchens, deeper loggias, higher floor-to-floor heights, and improved layouts with separate sanitary facilities. Modular building sections could be rotated and connected at different angles, allowing residential buildings to adapt to the varied topography [3].

The combination of stone, large-block, and large-panel construction created a diverse architectural environment that harmonized with the coastal landscape. Public buildings further reinforced the city's architectural identity through climate-responsive design elements characteristic of southern architecture, including shaded walls, internal courtyards, canopies, arcades, and solar-shading systems.

Major public buildings were conceived as parts of an integrated urban composition, sharing common architectural principles and repeated design motifs. Interior spaces also received considerable artistic attention. Buildings such as the Abai Palace of Culture and the Aktau Hotel incorporated monumental decorative art together with high-quality finishing materials, strengthening the cultural identity of the city [5].

Urban greening became one of the key components of Shevchenko's planning strategy. In the harsh desert environment, vegetation served not only aesthetic purposes but also improved the local microclimate by reducing dust, providing shade, and moderating temperatures. Despite difficult environmental conditions, approximately 10,000 trees and tens of thousands of shrubs and flowers were planted annually. Parks, boulevards, squares, fountains, and landscaped public spaces gradually transformed Shevchenko into what contemporary authors described as a "green oasis amid the sun-scorched desert" [3].

Pedestrian spaces also received careful attention. Sidewalks, plazas, and walkways were paved with concrete slabs of different sizes and textures, while decorative retaining walls integrated natural terrain into landscaped areas. Urban furniture and small architectural elements—including benches, lighting fixtures, kiosks, signs, and playground structures—

enhanced both the functionality and visual identity of public spaces. Their sculptural forms and bright colors introduced diversity and strengthened the city's architectural character [6].

Overall, the development of Shevchenko demonstrates how urban planning and architectural solutions can successfully respond to the challenges of an arid environment. Climate-responsive planning principles, functional zoning, the use of locally available materials, and comprehensive landscaping strategies made it possible to establish a sustainable and comfortable urban environment despite severe natural constraints. The experience of Shevchenko remains highly relevant for contemporary urban planning and architectural design in regions characterized by extreme climatic conditions.

Keywords: *Shevchenko, arid climate, architectural identity, urban planning solutions, climate-responsive architecture.*

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Biological Sciences

Peripheral Neuronal Biomarkers, REM-Sleep Neurophysiology, and Nanoparticle Drug Delivery: An Integrated Translational Framework for Brain Diagnosis and Therapy

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1. Abstract

Early diagnosis and effective treatment of central nervous system disorders remain constrained by the inaccessibility of brain tissue, the restrictive blood-brain barrier, and the delayed appearance of overt neurological symptoms. This review integrates three rapidly advancing domains that together offer a practical translational pathway for brain medicine: peripheral neuronal biomarkers, sleep neurophysiology, and nanoparticle-enabled drug delivery. Blood- and cerebrospinal-fluid biomarkers such as the amyloid-beta 42/40 ratio, phosphorylated tau isoforms, neurofilament light chain, glial fibrillary acidic protein, ubiquitin carboxyl-terminal hydrolase L1, exosomal cargo, and disease-associated microRNAs now provide minimally invasive windows into neurodegeneration, acute injury, and glioma biology. In parallel, mechanistic studies of rapid eye movement and non-rapid eye movement sleep show that REM architecture, hippocampal replay, spindle-ripple coupling, and glymphatic clearance act as informative physiological readouts of circuit integrity and cognitive vulnerability. Nanoparticle systems—including lipid, polymeric, and magnetic platforms—add the therapeutic dimension by enabling transport of nucleic acids, small molecules, and imaging agents across or around the blood-brain barrier, especially when paired with receptor targeting or focused ultrasound. When considered together, these areas support a stepwise model in which biomarkers identify risk and disease stage, sleep physiology refines timing and mechanistic interpretation, and nanocarriers deliver precision interventions while the same biomarkers track response. The resulting framework is particularly relevant to neurodegeneration, brain injury, and glioblastoma, where earlier detection and more selective delivery are both urgently needed.

Keywords: blood-based biomarkers; phosphorylated tau; neurofilament light chain; exosomes; REM sleep; hippocampal replay; glymphatic system; blood-brain barrier; lipid nanoparticles; focused ultrasound; glioblastoma; translational neuroscience

Introduction

Three rapidly advancing domains now offer that possibility. First, peripheral neuronal biomarkers measured in blood or extracellular vesicles can report molecular pathology long before conventional symptoms emerge. Plasma phosphorylated tau species, amyloid-beta ratios, neurofilament light chain, glial fibrillary acidic protein, ubiquitin carboxyl-terminal hydrolase L1, and vesicle-derived protein or microRNA signatures increasingly provide disease-specific and injury-related information at population scale (Janelidze et al., 2020; Karikari et al., 2020; Zetterberg and Blennow, 2021). Second, sleep neurophysiology has progressed from descriptive polysomnography to circuit-level models of rapid eye movement sleep, memory replay, spindle-ripple coupling, and glymphatic clearance. These processes are not merely epiphenomena; they shape protein homeostasis, synaptic remodeling, emotional regulation, and network resilience, and they may therefore identify optimal states for therapeutic intervention (Rasch and Born, 2013; Xie et al., 2013; Scammell et al., 2017). Third, nanotechnology has yielded lipid, polymeric, magnetic, and ligand-functionalized carriers capable of transporting nucleic acids, small molecules, and proteins into the brain by receptor-mediated transport, transient barrier opening, or state-dependent permeability modulation (Saraiva et al., 2016; Teleanu et al., 2018).

This review synthesizes these domains into a single translational framework. In that framework, peripheral biomarkers identify the disease, quantify its activity, and stratify risk; sleep physiology contributes timing, mechanistic context, and potentially modifiable biological windows; and nanoparticle systems execute targeted treatment by overcoming blood-brain barrier constraints. Although these literatures have often evolved in parallel, they increasingly share a common mechanistic vocabulary involving neuronal injury, glial function, network oscillation, interstitial fluid dynamics, endocytic transport, and longitudinal response monitoring. The practical implication is that integrated protocols may be more informative than siloed programs. A patient could, for example, undergo serial plasma p-tau217 and neurofilament light chain testing, coupled home sleep recording, and blood-brain barrier-targeted nanotherapy, with treatment timing adjusted to slow-wave sleep physiology and therapeutic response followed through repeated biomarker sampling (Jack et al., 2018; Janelidze et al., 2020).

The present article is structured as a scientific review. Sections 2 through 7 examine the rationale, molecular identities, and analytical platforms of peripheral neuronal biomarkers. Sections 8 through 14 review REM neurobiology, hippocampal replay, dream-related oscillations, spindle-based plasticity, and glymphatic clearance. Sections 15 through 18 evaluate major brain-directed nanoparticle strategies, including lipid nanoparticles, transferrin receptor targeting, magnetic systems, and focused ultrasound-assisted delivery. The final sections integrate these observations into a clinical pipeline intended to support earlier diagnosis, biologically timed intervention, and adaptive response monitoring across neurodegeneration, traumatic injury, and neuro-oncology.

2. Rationale and Biomarker Framework

The modern biomarker era in neurology emerged from the recognition that neuropathological change substantially precedes clinical symptoms. In Alzheimer's disease, amyloid deposition, tau dysregulation, synaptic dysfunction, and neuronal loss can develop over one to two decades

before dementia is diagnosed, making late-stage cognitive assessment a poor tool for prevention-oriented care. The amyloid-tau-neurodegeneration framework formalized the concept that these pathological dimensions can be measured separately and interpreted jointly, thereby shifting diagnosis from syndromic description to biological classification (Jack et al., 2018). The decisive translational question is not whether preclinical pathology exists, but whether it can be measured accurately and noninvasively enough to guide real-world care.

Blood-based biomarkers have transformed that question. Assays based on single molecule array technology, immunoprecipitation coupled to mass spectrometry, and increasingly multiplexed digital platforms now quantify analytes in the femtomolar range from a small volume of plasma or serum. Head-to-head comparisons against cerebrospinal fluid and positron emission tomography benchmarks repeatedly show strong concordance for the best-performing markers, especially when analytes are combined rather than interpreted in isolation (Janelidze et al., 2020; Palmqvist et al., 2020). This improvement matters because blood can be drawn in primary care, emergency settings, or longitudinal cohort studies with minimal burden, enabling repeated measurements that are impossible or impractical with lumbar puncture or repeated imaging.

A useful biomarker framework must satisfy at least four translational functions. First, it should detect pathology before irreversible disability becomes pronounced. Second, it should discriminate disease classes sufficiently to support differential diagnosis. Third, it should quantify severity or activity over time. Fourth, it should be analytically stable enough for use across laboratories and clinical populations. No single analyte fully satisfies all four criteria; consequently, multi-analyte panels are likely to dominate clinical practice. A pathology-specific signal such as p-tau217 can be combined with a more generic injury marker such as neurofilament light chain and a glial response marker such as GFAP to generate a richer disease map than any single test can provide (Ashton et al., 2021; Blennow et al., 2023).

The biomarker framework is equally important beyond Alzheimer's disease. Synucleinopathies, frontotemporal degeneration, multiple sclerosis, traumatic brain injury, and glioma all require tools that capture ongoing injury or molecular subtype with minimal invasiveness. In this sense, peripheral biomarkers are not simply substitutes for cerebrospinal fluid. They are enabling technologies for repeated disease-state sampling, trial enrichment, risk modeling, and treatment-response surveillance. Their true value may therefore lie as much in longitudinal trajectories as in one-time diagnostic classification.

3. Plasma Phosphorylated Tau

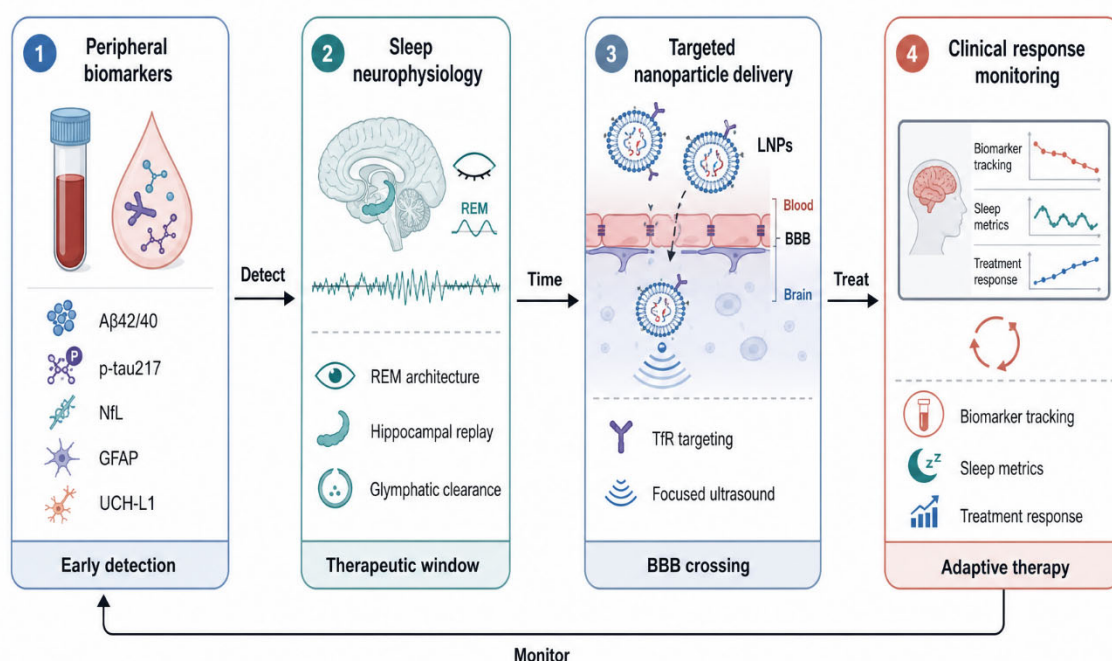
Among contemporary neuronal biomarkers, plasma phosphorylated tau has most dramatically altered the diagnostic landscape of Alzheimer's disease. Tau phosphorylated at threonine 181, 217, and 231 reflects abnormal tau metabolism and correlates with amyloid and tau pathology measured by cerebrospinal fluid or molecular imaging. Of these, p-tau217 has consistently shown the strongest separation between amyloid-negative and amyloid-positive individuals and the highest accuracy for distinguishing Alzheimer's disease from other dementias (Janelidze et al., 2020; Palmqvist et al., 2020). Plasma p-tau181 and p-tau231 remain valuable, particularly in early disease staging and cross-cohort comparison, but p-tau217 has emerged as the leading candidate for routine clinical deployment.

The biological interpretation of plasma p-tau is important. It does not merely indicate generalized neuronal death. Rather, it reflects disease-linked tau phosphorylation and release from neurons

in a context shaped by amyloid pathology, synaptic stress, and interstitial fluid exchange. This relative specificity explains why p-tau217 can separate Alzheimer's disease from frontotemporal dementia far better than total tau and why it correlates strongly with downstream cognitive decline and regional atrophy (Karikari et al., 2020; Blennow et al., 2023). Moreover, because plasma sampling is simple, serial measurements can track treatment-related change, an application of growing relevance as disease-modifying therapies enter clinical practice.

Analytical advances explain much of the clinical momentum. Single molecule array platforms, mass spectrometry methods, and next-generation immunoassays now detect p-tau at extremely low concentrations with improving between-laboratory reproducibility. When plasma p-tau217 is combined with the amyloid-beta 42/40 ratio, diagnostic performance in mixed cohorts often reaches levels once considered achievable only with cerebrospinal fluid or imaging-based workflows (Janelidze et al., 2020; Zetterberg and Blennow, 2021). This supports a near-term model in which blood testing serves as the first-line biological screen, reserving more invasive or expensive confirmation for borderline cases, unusual phenotypes, or therapeutic decision points.

Several caveats remain. Age, renal function, comorbidity burden, and assay harmonization affect interpretation. Plasma p-tau is also less informative outside tau-related pathology, meaning it should not be used as a generic brain disease marker. Yet even with these limitations, plasma p-tau217 is arguably the most consequential diagnostic advance in dementia medicine of the last decade because it compresses pathology detection, prognostic stratification, and longitudinal monitoring into a scalable outpatient test (Fig 1).



Integrated translational framework for brain diagnosis and therapy

Figure 1. Integrated translational framework for brain diagnosis and therapy. The schematic summarizes a four-step translational pipeline linking peripheral neuronal biomarkers, sleep neurophysiology, targeted nanoparticle delivery, and clinical response monitoring. Peripheral biomarkers such as Aβ42/40, p-tau217, NfL, GFAP, and UCH-L1 support early detection. Sleep neurophysiology contributes mechanistic and timing information through REM architecture,

hippocampal replay, and glymphatic clearance. Targeted nanocarriers, including LNPs, TFR-targeted systems, and focused ultrasound-assisted delivery, enable blood-brain barrier crossing and therapeutic intervention. Clinical response monitoring then feeds back into adaptive therapy through repeated biomarker and sleep-based assessment. This concept follows the manuscript's integrated framework in which biomarkers identify disease, sleep physiology helps define the therapeutic window, and nanocarriers execute treatment.

4. Neurofilament Light Chain as a Universal Injury Marker

Neurofilament light chain occupies a different but equally important niche. As a structural component of the axonal cytoskeleton, neurofilament light chain is released when axons are injured or undergo active degeneration. Peripheral elevations therefore reflect neuronal damage across a broad spectrum of disorders rather than a single disease-specific cascade. This lack of specificity is a limitation for diagnosis, but a strength for monitoring, because neurofilament light chain functions as a general index of neurobiological injury burden (Khalil et al., 2018; Zetterberg and Blennow, 2021).

In familial and sporadic Alzheimer's disease, plasma or serum neurofilament light chain rises years before symptom onset and predicts faster subsequent decline. Similar associations have been reported in multiple sclerosis, amyotrophic lateral sclerosis, Parkinson's disease, frontotemporal dementia, Huntington's disease, and traumatic brain injury. In many settings, the longitudinal slope of neurofilament light chain is more informative than a single measurement, indicating whether active tissue injury is accelerating, stabilizing, or responding to therapy (Khalil et al., 2018). This makes the marker particularly valuable in clinical trials of antisense oligonucleotides, monoclonal antibodies, or anti-inflammatory interventions, where a scalable readout of neuronal preservation is needed.

The marker's universality, however, imposes interpretive discipline. Age strongly influences baseline concentrations, and body mass index, renal clearance, and systemic illness can confound apparent disease effects. Standardized reference intervals and model-based interpretation are therefore essential if neurofilament light chain is to be used outside highly controlled research cohorts. Even so, its translational utility is considerable. A generic injury marker complements disease-specific analytes precisely because it can reveal whether an apparently targeted therapy is actually reducing axonal damage in the living patient.

5. Exosomes and MicroRNA as Emerging Biomarkers

Extracellular vesicles, especially exosomes, extend biomarker science beyond soluble proteins. These vesicles carry cargo derived from their parent cells, including proteins, lipids, messenger RNA, and microRNA, and are shielded from enzymatic degradation by a lipid membrane. Neuron-derived or glia-enriched exosomes isolated from blood therefore offer a plausible route for sampling brain-origin molecular states without direct access to brain tissue or cerebrospinal fluid (Fiandaca et al., 2015; Pulliam et al., 2019). In Alzheimer's disease, vesicular tau, amyloid-related proteins, synaptic markers, and inflammatory signals have all been studied as potential indicators of preclinical change.

MicroRNAs further increase the dimensionality of this approach. Disease-associated patterns involving miR-29 family members, miR-146a, miR-21, and other small noncoding RNAs have been

linked to Alzheimer's disease, Parkinson's disease, glioblastoma, and neuroinflammatory states. In neuro-oncology, exosomal cargo is particularly attractive because tumor-derived vesicles can carry molecular subtype information such as EGFRvIII-related signatures, potentially reducing dependence on repeated invasive biopsy (Skog et al., 2008). In principle, vesicle-based biomarkers could support both diagnosis and therapeutic targeting by identifying which molecular programs are active in a given patient at a given time.

Clinical translation remains more challenging than for soluble protein assays. Vesicle isolation methods differ across laboratories, enrichment of brain-derived vesicles is imperfect, and pre-analytical variables can distort apparent cargo abundance. Nonetheless, exosomes and microRNA are important because they move biomarker science from single-analyte monitoring toward distributed molecular phenotyping. Over time, they may provide the link between simple blood testing and genuinely personalized intervention.

6. Acute Injury Biomarkers and Multi-Analyte Triage

Acute neurology requires rapid decisions under uncertainty, and peripheral biomarkers are increasingly entering that space. Glial fibrillary acidic protein reflects astroglial injury, whereas ubiquitin carboxyl-terminal hydrolase L1 reflects neuronal cell-body damage. Together, these markers improve the triage of mild traumatic brain injury by helping predict whether intracranial lesions are likely to be visible on computed tomography, thereby reducing unnecessary imaging in low-risk patients while preserving safety-sensitive detection (Bazarian et al., 2018). In subacute settings, GFAP, UCH-L1, neurofilament light chain, and tau-related markers may also predict persistent symptoms, delayed recovery, or the transition from acute insult to chronic neurodegenerative vulnerability.

The broader significance of these markers lies in continuum thinking. Brain injury does not fall into neatly isolated bins of trauma, degeneration, and inflammation. Rather, it unfolds across overlapping temporal and molecular axes. A panel that measures astroglial reactivity, neuronal injury, axonal degeneration, and disease-specific pathology can therefore support emergency triage, subacute monitoring, and long-term risk assessment within a unified framework. Such a framework is especially appealing in older adults, where mild traumatic brain injury may intersect with preclinical neurodegeneration and where biomarker interpretation must distinguish acute insult from chronic pathology.

7. Analytical Platforms and Pre-Analytical Standardization

The clinical value of any biomarker depends as much on measurement reliability as on biological meaning. Single molecule array technology, often abbreviated Simoa, has become foundational because it enables digital counting of individual immunocomplexes at femtomolar concentrations. Cartridge-based platforms such as Ella provide streamlined workflow and reduced operator burden, whereas immunoprecipitation coupled to liquid chromatography-mass spectrometry offers absolute peptide quantification and high specificity for structurally similar analytes (Blennow et al., 2023). Newer barcoded or multiplex systems are pushing detection lower while allowing simultaneous measurement of several markers from a single small specimen.

Yet analytical sensitivity alone is insufficient. Collection tube chemistry, delay to centrifugation, storage temperature, freeze-thaw exposure, hemolysis, anticoagulant choice, and matrix effects can all shift measured concentrations enough to obscure clinically meaningful differences. This is

particularly problematic when disease effects are modest or when longitudinal change is being used to infer therapeutic efficacy. Standardization initiatives led by international consortia therefore aim to harmonize sample collection, processing, calibration, reporting, and external quality assessment (Teunissen et al., 2022).

The future of clinical biomarker deployment will likely be multiplex, longitudinal, and algorithmically interpreted. Rather than asking whether a single value crosses a universal threshold, clinicians will increasingly evaluate pattern-based trajectories that incorporate age, renal function, body composition, genotype, disease context, and prior measurements. That approach is analytically more demanding, but it aligns with the true biology of brain disease and is essential if peripheral biomarkers are to serve as the diagnostic backbone of integrated translational neuroscience.

8. Sleep Architecture and the Cellular Basis of REM

Sleep architecture provides more than a behavioral background state; it organizes neuronal excitability, synaptic homeostasis, memory processing, and interstitial fluid dynamics. In healthy adults, sleep alternates between non-rapid eye movement and rapid eye movement phases across approximately ninety-minute cycles. NREM stage N3 is characterized by slow oscillations and high-amplitude delta activity generated by coordinated thalamocortical and corticocortical networks, whereas REM sleep combines cortical activation, rapid eye movements, vivid mentation, autonomic variability, and profound skeletal muscle atonia (Scammell et al., 2017; Saper et al., 2010). This paradoxical combination of activation and paralysis makes REM a uniquely informative state for both systems neuroscience and clinical neurology.

At the cellular level, REM depends on interactions among pontine, medullary, hypothalamic, basal forebrain, and cortical populations. Cholinergic activation rises, monoaminergic firing from the locus coeruleus and dorsal raphe falls dramatically, and descending pathways suppress spinal motor output to generate atonia. The resulting brain state favors internally generated activity patterns, sensory decoupling, and limbic activation. Clinically, the architecture of REM matters because it is altered early in several brain disorders. Changes in REM density, latency, fragmentation, and motor control may precede overt motor or cognitive symptoms in synucleinopathies, mood disorders, post-traumatic states, and neurodegeneration more broadly (Peever and Fuller, 2017).

The translational importance of sleep architecture lies in its interpretability. It is measurable noninvasively through polysomnography, increasingly capturable through ambulatory devices, and tightly linked to neuromodulatory and glymphatic processes relevant to disease progression. In an integrated clinical framework, sleep stages should be considered physiological windows that influence both disease expression and therapeutic opportunity rather than passive background states (Fig 2).

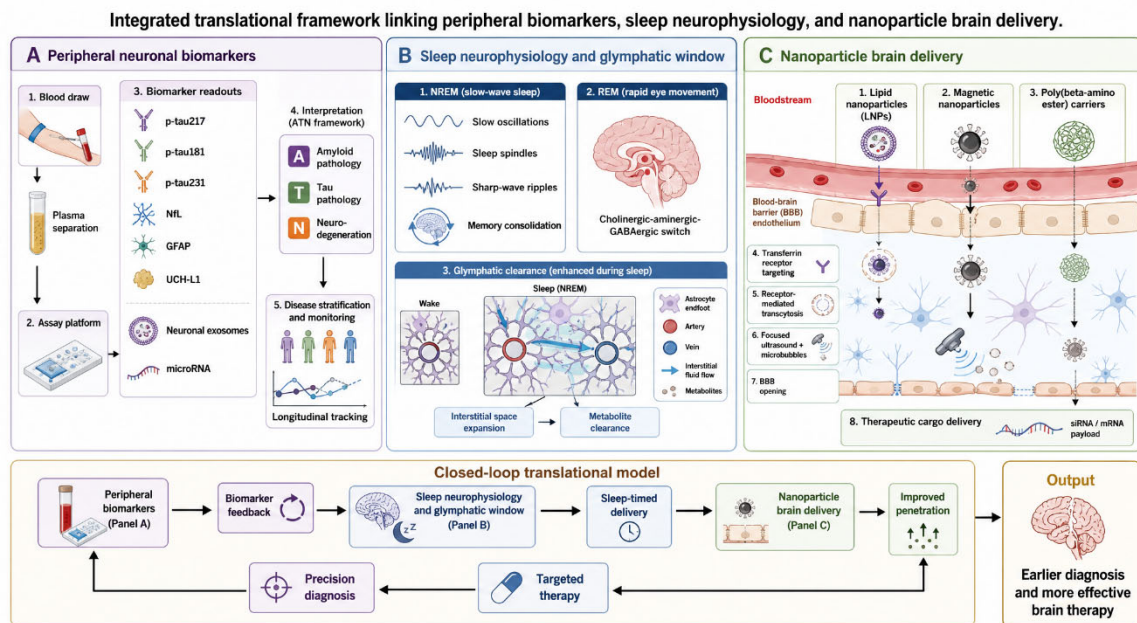


Figure 2. Integrated translational framework linking peripheral biomarkers, sleep neurophysiology, and nanoparticle brain delivery. The schematic summarizes a closed-loop strategy for brain diagnosis and therapy. The left panel shows peripheral neuronal biomarker assessment from blood, including p-tau217, p-tau181, p-tau231, neurofilament light chain (NFL), GFAP, UCH-L1, neuronal exosomes, and microRNA, enabling disease stratification and longitudinal monitoring. The center panel illustrates sleep neurophysiology as both a diagnostic readout and a therapeutic window, highlighting NREM-associated slow oscillations, sleep spindles, sharp-wave ripples, memory consolidation, REM-state circuitry, and glymphatic interstitial fluid clearance. The right panel depicts nanoparticle-mediated brain delivery across the blood-brain barrier using lipid nanoparticles, magnetic nanoparticles, and poly(beta-amino ester) carriers, together with transferrin receptor targeting, receptor-mediated transcytosis, and focused ultrasound plus microbubbles. The bottom integration band emphasizes biomarker feedback, sleep-timed delivery, improved parenchymal penetration, precision diagnosis, and targeted therapy, converging on earlier diagnosis and more effective treatment of brain disease

9. Cholinergic Mechanisms Underlying REM Sleep

The cholinergic basis of REM sleep remains one of the most durable principles in sleep neurobiology. Neurons in the pedunculopontine and laterodorsal tegmental nuclei project widely to the thalamus, basal forebrain, hypothalamus, and brainstem, and their increased activity contributes to cortical activation, ponto-geniculo-occipital waves, and the internally oriented sensory dynamics that define REM sleep (Brown et al., 2012; Scammell et al., 2017). Acetylcholine also modulates hippocampal theta rhythm, a central oscillatory component of mnemonic processing and dream-related network integration.

This cholinergic system has direct disease relevance. In Parkinson's disease and related synucleinopathies, cholinergic dysfunction contributes to REM sleep behavior disorder, gait disturbance, attentional fluctuation, and cognitive decline. REM sleep behavior disorder, in which the normal atonia of REM fails and dream enactment appears, is now recognized as one of the most powerful prodromal markers of alpha-synuclein pathology (Postuma et al., 2019). The significance of this observation for the present review is twofold. First, REM alterations can act as early physiological biomarkers of brainstem neurodegeneration. Second, the underlying cholinergic circuitry offers mechanistic information that complements molecular assays. A patient

with abnormal plasma injury markers and prodromal REM dysregulation may have a very different trajectory from a patient with molecular biomarker positivity but preserved sleep-state control.

Pharmacological work further supports the centrality of cholinergic signaling. Agents that enhance cholinergic tone can influence REM propensity and dream vividness, whereas lesions of pontine cholinergic nuclei or their downstream effectors distort REM organization. Although cholinergic manipulation alone is unlikely to solve neurodegeneration, it illustrates how circuit-level physiology can be used to interpret biomarker-defined disease states.

10. Reciprocal Interactions and the Aminergic-Cholinergic Switch

Classical reciprocal interaction models proposed that REM onset arises when cholinergic excitation increases while aminergic inhibition from norepinephrine- and serotonin-producing neurons withdraws (Hobson et al., 1975). Contemporary circuit models refine this view by incorporating GABAergic REM-on populations, glutamatergic coordination, hypothalamic influences, and distributed inhibitory microcircuits that stabilize transitions between sleep states (Saper et al., 2010; Brown et al., 2012). Even with these refinements, the essential principle remains: REM is produced by a carefully balanced switch in neuromodulatory regime rather than by a single isolated trigger.

This switching framework is clinically useful because unstable transitions leave measurable traces. REM fragmentation, altered muscle atonia, and abnormal phasic events may reflect diseased circuits long before structural imaging becomes diagnostic. Because locus coeruleus degeneration can occur early in Alzheimer's disease and because aminergic-cholinergic balance influences arousal, emotional memory, and autonomic output, REM metrics may serve as sensitive systems-level markers of network vulnerability (Braak and Del Tredici, 2015). More importantly, state transitions may affect blood-brain barrier physiology, glymphatic exchange, and drug distribution, suggesting that the sleep cycle could be incorporated directly into treatment timing.

In translational terms, the REM switch offers a bridge concept between molecular pathology and therapeutic delivery. Biomarkers can define who is at risk, but sleep-state transitions may help define when a targeted intervention should be delivered for maximal neural accessibility and minimal physiological disruption.

11. Hippocampal Replay and Memory Consolidation

Hippocampal replay refers to the reactivation of neuronal firing sequences that were expressed during prior waking experience. In rodents, place-cell assemblies reactivate during sharp-wave ripple events in quiet wakefulness and NREM sleep, supporting the transfer and stabilization of recent memories across hippocampal-neocortical networks (Wilson and McNaughton, 1994; Ji and Wilson, 2007). In humans, convergent electrophysiological and imaging work indicates that ripple-associated replay and large-scale network coordination contribute to episodic memory consolidation, spatial abstraction, and schema formation (Rasch and Born, 2013).

Although replay is most strongly associated with NREM sharp-wave ripples, REM contributes complementary functions, including synaptic integration, emotional salience assignment, and associative recombination. The meaningful point for translational neuroscience is that memory consolidation is not a monolithic process. It is distributed across sleep stages, oscillatory modes, and interacting circuit motifs. Neurodegeneration that disrupts hippocampal replay, spindle-ripple

coupling, or REM-associated theta organization may therefore impair cognition before standard neuropsychological testing fully captures the deficit.

Replay is also relevant as a mechanistic biomarker. If peripheral markers indicate incipient Alzheimer's disease and sleep physiology shows degraded replay-related coupling, the combination yields a richer picture of disease expression than either domain alone. In future studies, replay-sensitive electrophysiology could be used not only to understand cognitive decline but also to evaluate whether biomarker-guided therapies restore network-level function.

12. Dream Generation and Oscillatory Correlates

Dreaming is often treated as an elusive subjective phenomenon, yet it is increasingly linked to identifiable oscillatory and regional activation patterns. REM sleep is associated with sustained theta activity, limbic engagement, visual association cortex activation, and relative deactivation of executive control regions, creating a neurophysiological environment conducive to vivid, emotionally charged, and often bizarre internal narratives (Siclari et al., 2017). Theta coherence between hippocampal and medial prefrontal regions has been associated with successful dream recall, while gamma activity may contribute to perceptual vividness and local integrative processing.

The clinical relevance of dream neurophysiology lies less in dream symbolism than in network integrity. Changes in dream recall, dream enactment, nightmare prevalence, or the spectral signatures associated with dream-rich sleep can reflect altered cholinergic function, limbic dysregulation, trauma-related hyperarousal, or prodromal synucleinopathy. Because dream-related measures can be acquired with relatively low-cost behavioral tools and coupled to electrophysiological recordings, they may eventually serve as auxiliary markers in longitudinal studies of early neurodegeneration, psychiatric disease, and post-injury recovery.

In the present framework, dream generation is not a peripheral curiosity. It is a readout of internally coordinated network function, positioned at the intersection of REM circuitry, memory processing, and emotional regulation. If coupled to blood-based biomarkers, dream-related physiology could provide an accessible systems-level indicator of whether a molecularly defined disease process is already altering higher-order brain function.

13. Sleep Spindles and Thalamocortical Coupling

Sleep spindles are transient 12 to 16 hertz oscillations generated through interactions between thalamic reticular neurons and thalamocortical relay systems. They are classically associated with stage N2 sleep, but their functional significance extends across the architecture of memory-related coordination because they help gate plasticity, protect sleep continuity, and synchronize corticothalamic communication (Rasch and Born, 2013). Increasing evidence suggests that the coupling of slow oscillations, spindles, and hippocampal ripples provides a mechanistic scaffold for offline consolidation of declarative memory.

Disruption of spindle density, timing, or cross-frequency coupling is reported in aging, schizophrenia, Alzheimer's disease, and other disorders of cortical-thalamic communication. For dementia research, spindle impairment may be especially important because it can reflect early circuit dysfunction before irreversible neuronal loss becomes radiologically obvious. When considered alongside peripheral biomarkers, spindle measures may help discriminate molecular

positivity with preserved network compensation from molecular positivity accompanied by active systems-level failure.

Thalamocortical coupling therefore belongs in any integrated model of brain diagnosis and therapy. It indexes one of the core physiological processes through which the sleeping brain reorganizes information, regulates excitability, and potentially modulates interstitial clearance. Therapeutic systems that aim to exploit sleep-state timing for drug delivery should account not only for broad sleep stages but also for the microstructure of oscillatory coordination within those stages.

14. Glymphatic Clearance and the Sleep-Wake Rhythm

The glymphatic pathway offers a compelling mechanistic link between sleep physiology and neurodegenerative risk. Cerebrospinal fluid enters the brain along periarterial routes, exchanges with interstitial fluid through aquaporin-4-dependent astroglial mechanisms, and exits along perivenous pathways carrying metabolic waste products, including amyloid-beta and tau-related material (Iliff et al., 2012; Jessen et al., 2015). Experimental work demonstrated that interstitial space expands substantially during sleep or anesthesia and that this expansion is associated with markedly enhanced clearance of solutes from the brain parenchyma (Xie et al., 2013).

This observation changed the conceptual status of sleep in neurology. Sleep is not merely restorative in a vague behavioral sense; it appears to regulate the physical removal of neurotoxic metabolites. Chronic sleep fragmentation, reduced slow-wave sleep, altered aquaporin-4 polarization, vascular stiffness, and aging-related astroglial changes may all weaken glymphatic efficiency and thereby increase vulnerability to protein aggregation disorders (Nedergaard and Goldman, 2020). Conversely, improving sleep continuity or aligning interventions with periods of maximal interstitial exchange may enhance both endogenous clearance and exogenous delivery.

From a translational standpoint, glymphatic biology supports three major propositions. First, sleep disruption may be a causal contributor to neurodegeneration rather than a secondary symptom alone. Second, sleep metrics should be integrated into biomarker interpretation because molecular burden and clearance capacity are biologically coupled. Third, the pharmacokinetics of brain-directed therapies may vary across the sleep-wake cycle. These propositions make glymphatic clearance central to the idea that sleep can define a therapeutic window in biomarker-guided neuroscience.

15. Background and Rationale for Nanoparticle Delivery

If biomarkers solve the problem of early detection, drug delivery remains the major obstacle to effective intervention. The blood-brain barrier is formed by endothelial tight junctions, pericytes, astrocytic end-feet, basement membrane specializations, and active transporter systems that collectively protect neural tissue from toxins and immune noise but also exclude most therapeutics (Pardridge, 2012). Large biologics, nucleic acids, and many small molecules fail to accumulate in brain tissue at useful concentrations after systemic administration. Nanoparticle systems emerged in response to this bottleneck because they can package cargo, shield it from degradation, alter circulation time, and exploit receptor-mediated transport or transient barrier modulation to improve delivery (Saraiva et al., 2016; Teleanu et al., 2018).

The major classes include lipid nanoparticles, polymeric nanoparticles, dendrimers, extracellular vesicles, and inorganic systems such as iron oxide or gold-based constructs. Their translational appeal derives from modularity. Particle size, surface charge, PEGylation, ligand decoration,

release kinetics, and imaging compatibility can all be tuned according to therapeutic need. Importantly, these design features are not only engineering variables; they shape biodistribution, immune recognition, endosomal escape, and toxicity.

In the context of brain disease, nanoparticle design must be aligned with pathophysiology. Diffuse neurodegeneration may require repeated low-toxicity delivery of gene-silencing or protein-modifying cargo across largely intact barrier tissue. Glioblastoma may permit partial exploitation of tumor-associated leakiness but still suffers from profound intratumoral heterogeneity and poor penetration. Traumatic brain injury presents dynamic changes in vascular permeability and inflammatory signaling that may create narrow windows for targeted intervention. A rational delivery program therefore depends on biomarker-defined disease state and, potentially, sleep-state-defined permeability or clearance conditions.

16. Lipid Nanoparticles and Small Interfering RNA Delivery

Lipid nanoparticles are the most clinically mature class of nonviral nucleic acid carriers and have gained enormous credibility through the success of messenger RNA therapeutics outside neurology. Typical formulations include ionizable lipids, cholesterol, helper phospholipids, and PEG-lipids that stabilize circulation while enabling endosomal escape after cellular uptake. For brain-directed use, lipid nanoparticles are attractive because they can encapsulate small interfering RNA, messenger RNA, antisense cargo, or small molecules in a scalable manufacturing framework compatible with regulatory development (Cullis and Hope, 2017).

The central challenge is traversing the blood-brain barrier. Several strategies have been explored, including surface functionalization with ligands that engage endothelial receptors, exploitation of adsorptive or receptor-mediated transcytosis, and delivery in disease states where the barrier is regionally disrupted. Preclinical studies have shown that appropriately engineered lipid nanoparticles can deliver gene-silencing cargo into glioma models, inflammatory lesions, and injury-modified brain tissue, sometimes producing measurable reductions in target expression and improved functional outcomes (Saraiva et al., 2016; Teleanu et al., 2018). Poly(beta-amino ester) systems and other hybrid lipid-polymer platforms further broaden the design space by combining strong nucleic acid complexation with biodegradable release.

For translational neuroscience, the appeal of lipid nanoparticles is that they are not speculative laboratory curiosities. They are manufacturable, chemically versatile, and increasingly understandable in pharmacokinetic terms. If paired with biomarker-based patient selection and sleep- or ultrasound-informed delivery timing, they could enable repeated outpatient administration of molecular therapies that were previously confined to invasive intrathecal or intraparenchymal approaches.

17. Magnetic Nanoparticles and Transferrin Receptor Targeting

Magnetic nanoparticles, most commonly based on iron oxide cores, occupy a distinctive position because they can combine therapy, targeting, and imaging within a single platform. Their magnetic properties support external guidance or hyperthermic applications, while their surfaces can be decorated with ligands that engage transport systems on brain endothelium or tumor cells. Among these, transferrin receptor targeting has received sustained attention because the receptor is abundantly expressed on blood-brain barrier endothelial cells and participates in receptor-mediated transcytosis (Johnsen et al., 2019).

Transferrin- or antibody-based targeting strategies can increase endothelial uptake, although success depends on epitope selection, binding affinity, particle geometry, and trafficking fate. Excessively strong binding may promote lysosomal sequestration rather than transcytosis, whereas appropriately tuned interactions may improve brain exposure without unacceptable off-target retention. Magnetic systems add a second level of controllability because external fields or alternating magnetic stimulation can influence localization or generate focal hyperthermia in tumor settings (Arruebo et al., 2007).

In glioma, this dual functionality is especially appealing. A particle can theoretically deliver chemotherapeutic or gene-silencing payloads, provide magnetic resonance contrast, and support adjunctive hyperthermia. In neurodegeneration, magnetic carriers may be more limited by diffuse target distribution, but they still illustrate the broader principle that blood-brain barrier transport can be engineered rather than passively endured. Their greatest value may lie in combined diagnostic-therapeutic paradigms where imaging, targeting, and treatment feedback are integrated from the outset.

18. Focused Ultrasound and Transient Blood-Brain Barrier Opening

Focused ultrasound with circulating microbubbles provides one of the most compelling methods for transiently and noninvasively increasing blood-brain barrier permeability. When low-intensity ultrasound is applied under imaging guidance, oscillating microbubbles interact mechanically with the vascular endothelium, creating a temporary and spatially controlled opening that can enhance brain delivery of drugs, antibodies, nanoparticles, and potentially cellular or genetic payloads (Hynynen et al., 2001; Lipsman et al., 2018). Because the effect is localizable and reversible, focused ultrasound offers a crucial advantage over nonspecific systemic barrier disruption.

Clinical studies in Alzheimer's disease, glioblastoma, and other conditions suggest that repeated blood-brain barrier opening can be performed safely when acoustic exposure is carefully monitored. Importantly, focused ultrasound is not merely a standalone procedure; it is a platform technology that can be combined with lipid nanoparticles, polymeric carriers, immunotherapy, or RNA-based medicines. In this sense, it converts the blood-brain barrier from a fixed obstacle into a timed, image-guided gateway.

Within the integrated framework proposed here, focused ultrasound is particularly valuable because it can be synchronized with biomarker monitoring and potentially with sleep physiology. A trial could, for example, enroll patients with rising plasma p-tau217, perform serial sleep assessments to characterize slow-wave integrity, and deliver nanoparticle cargo through ultrasound-assisted opening during a biologically optimized treatment schedule. Such an approach would directly test whether molecular disease state, brain-state physiology, and engineered access can be coordinated in the same patient.

19. Integrated Translational Framework

The three domains reviewed above converge into a coherent translational pipeline when considered jointly rather than sequentially. Peripheral biomarkers identify disease biology, quantify progression, and provide repeated response readouts. Sleep neurophysiology reveals circuit vulnerability, glymphatic capacity, and state-dependent windows relevant to both disease expression and therapeutic timing. Nanoparticle systems provide the practical means to cross the

blood-brain barrier and act on targets that would otherwise remain inaccessible. The central thesis is therefore simple: diagnosis, timing, and delivery should be designed as an integrated program, not as isolated technical problems.

A clinically plausible pathway would begin with screening using blood-based markers such as amyloid-beta 42/40, p-tau217, neurofilament light chain, GFAP, or disease-specific vesicle signatures. Individuals flagged as high risk could then undergo sleep phenotyping, ranging from home actigraphy and sleep questionnaires to polysomnography or high-density electrophysiology in research settings. Sleep measures would not merely confirm symptoms; they would indicate whether REM regulation, spindle-ripple coupling, slow-wave depth, or glymphatic opportunity are already altered. Therapy would then be tailored accordingly. A patient with molecular evidence of early Alzheimer's disease and preserved slow-wave sleep may be suited to one delivery schedule, whereas a patient with severe sleep fragmentation and impaired REM architecture may require simultaneous sleep-directed intervention.

This integrated logic suggests at least five translational priorities. First, blood-based biomarker panels should be embedded prospectively into sleep-physiology and focused-ultrasound trials so that biological efficacy can be measured alongside symptoms. Second, longitudinal biomarker trajectories should be correlated with glymphatic and oscillatory measures to test whether impaired sleep-state physiology predicts molecular worsening. Third, REM abnormalities, melatonin rhythm disruption, and dream-enactment phenotypes should be studied as physiological risk signals in biomarker-positive but clinically pre-symptomatic cohorts. Fourth, the pharmacokinetics of nanoparticle delivery should be mapped across sleep-wake states to determine whether slow-wave sleep or adjacent windows improve brain penetration or retention. Fifth, combined delivery strategies, especially lipid nanoparticles plus focused ultrasound, should be optimized to maximize parenchymal dosing while minimizing systemic toxicity.

The intellectual value of this model is its refusal to separate molecular pathology from physiological context. The practical value is even greater: each component is already close enough to clinical reality to be combined experimentally within the present decade.

20. Conclusions and Future Directions

Peripheral biomarkers, sleep neurophysiology, and engineered nanocarriers together represent one of the most dynamic translational frontiers in modern neuroscience. Blood-based assays are steadily reducing dependence on invasive cerebrospinal fluid sampling and expensive imaging; sleep research is redefining disease mechanisms by linking circuit oscillations, glymphatic clearance, and neurodegenerative risk; and brain-directed nanoparticle systems are turning once-impractical therapies into clinically testable interventions (Jack et al., 2018; Xie et al., 2013; Pardridge, 2012). The convergence of these fields supports a new model of neurological care built on early detection, physiological timing, targeted delivery, and repeated quantitative monitoring.

Several principles should guide future work. Biomarker programs must prioritize harmonization, demographic diversity, and real-world implementation rather than remaining confined to specialist centers. Sleep research must move beyond descriptive staging toward mechanism-informed metrics that can be standardized and scaled. Nanoparticle development must focus not only on proof-of-concept delivery but also on manufacturability, toxicity, dosing logic, and patient selection. Most importantly, clinical trials should be explicitly cross-domain. A therapy delivered across the blood-brain barrier without molecular enrichment is inefficient; a biomarker detected

without a delivery strategy is inert; and a sleep-based therapeutic window identified without a treatable target is clinically incomplete.

The next decade should therefore be defined by integrated study design. Memory-clinic cohorts should incorporate sleep metrics and delivery readiness. Neuro-oncology trials should include blood-based molecular monitoring. Traumatic brain injury programs should connect acute biomarkers with later sleep-state and cognitive outcomes. Across these settings, adaptive algorithms could use serial biomarkers and physiological readouts to refine timing, dose, and therapeutic modality in individual patients.

If successful, this agenda would alter the natural history of central nervous system disease. Conditions once recognized only after major injury could be identified during their preclinical phase. Therapies now blocked by the blood-brain barrier could be delivered with increasing precision. Treatment response could be tracked in weeks rather than inferred after years of decline. Such progress will require rigorous validation, interdisciplinary collaboration, and careful attention to equity and safety. Nevertheless, the path forward is now visible: the future of brain diagnosis and therapy lies in coupling molecular evidence, physiological state, and engineered access within one coordinated translational framework.

21. Clinical Translation, Trial Design, and Implementation Barriers

The promise of an integrated biomarker-sleep-delivery framework will only be realized if studies are designed to test interaction effects rather than isolated endpoints. Traditional neurology trials often separate diagnostic enrichment from physiological phenotyping and from pharmacokinetic optimization. In the proposed model, however, those elements should be linked prospectively. A prevention-oriented Alzheimer's trial, for instance, should not merely recruit participants with elevated plasma p-tau217; it should also characterize sleep continuity, slow-wave activity, and REM integrity at baseline, because these physiological features may help determine whether amyloid- or tau-directed therapy reaches a vulnerable but still modifiable network state (Jack et al., 2018; Teunissen et al., 2022). Likewise, studies of focused ultrasound or nanoparticle-mediated delivery should not treat target engagement as independent from biological timing. If drug entry, clearance, or interstitial dispersion varies across the sleep-wake cycle, then trial design must incorporate time-of-day and sleep-state variables from the beginning rather than as exploratory afterthoughts.

This requirement changes several aspects of translational methodology. Enrollment criteria should move from diagnosis alone to multimodal staging. Endpoints should include not only cognitive scores or radiographic change but also serial plasma markers, oscillatory sleep metrics, and delivery-associated safety biomarkers. Adaptive designs may be particularly suitable because they allow modification of dosing interval, sonication schedule, or supportive sleep interventions according to emerging biological response. Such adaptability is already routine in oncology and should become more common in neurology, especially when the measured signals are dynamic and interdependent.

Implementation barriers remain substantial. Blood-based assays still require broader assay harmonization, cut-point validation across diverse ancestral groups, and operational guidance for primary care use. Sleep measurement faces a different but equally serious scaling challenge: polysomnography is information-rich yet expensive and labor-intensive, whereas wearable devices are scalable but less precise for microstructural physiology. Nanoparticle therapies add

still another layer of complexity, including manufacturing reproducibility, immunogenicity, carrier-specific toxicity, cargo stability, and uncertainty regarding repeated long-term administration. Focused ultrasound, although increasingly mature, depends on specialized infrastructure, image guidance, and acoustic safety monitoring that are currently concentrated in tertiary centers (Lipsman et al., 2018).

Regulatory pathways will therefore need to evolve. A combined platform in which a blood test enriches the population, a sleep-derived metric defines timing, and a nanoparticle or ultrasound procedure delivers therapy does not fit neatly into legacy silos separating diagnostics, devices, and drugs. Regulators and trial sponsors may need co-development strategies in which the biomarker panel, the physiological monitoring method, and the delivery platform are validated as a linked clinical system. That complexity should not be viewed as a reason for delay. On the contrary, it reflects the biological reality of brain disease, where pathology, state, and access are inseparable.

Equity considerations are also critical. One of the strongest arguments for blood-based biomarkers is their potential to decentralize neurological risk detection beyond specialized academic centers. If, however, downstream sleep phenotyping and delivery technologies remain available only to highly resourced institutions, the translational gains will be unevenly distributed. Future implementation programs should therefore emphasize tiered workflows. Community settings may begin with plasma screening and low-burden sleep assessment, with referral of selected patients for advanced electrophysiology or image-guided delivery. Such tiering would preserve precision while maintaining accessibility. Without that step, the field risks reproducing the same disparities that historically limited cerebrospinal fluid testing and advanced neuroimaging to narrow patient populations.

Finally, there is a conceptual barrier that deserves explicit attention: many neurological disorders do not follow a single linear pathway. Alzheimer's disease may coexist with vascular injury, Lewy body pathology, sleep apnea, chronic inflammation, or traumatic exposure. A flexible integrated framework is therefore preferable to a disease-specific rigid algorithm. The point is not to force every patient into the same pathway, but to create a shared translational language through which molecular evidence, physiological state, and delivery opportunity can be combined in a clinically meaningful manner. In that sense, the integrated framework proposed here is both a scientific model and a practical organizing principle for the next generation of neuroscience trials.

22. Outlook for Precision Neurotherapeutics

The long-term significance of this field lies in the emergence of precision neurotherapeutics. In oncology, personalized treatment became possible when molecular classification, imaging, and targeted intervention began to inform one another continuously. Neurology has lagged because the brain is less accessible and because many disorders unfold across years before clear structural damage appears. Peripheral biomarkers, sleep neurophysiology, and engineered delivery systems may collectively overcome that lag. They offer a way to classify disease early, interpret its systems-level expression, and intervene with molecular specificity while the tissue remains salvageable (Blennow et al., 2023; Pardridge, 2012).

In practical terms, a precision model might proceed as follows. A middle-aged adult with subtle subjective cognitive complaints undergoes blood testing in primary care and is found to have an abnormal amyloid-beta 42/40 ratio and borderline elevation of p-tau217. Rather than waiting for clinically obvious impairment, the patient enters a structured risk pathway that includes sleep

evaluation, vascular profiling, and repeated biomarker measurement over time. If the molecular trajectory worsens and slow-wave sleep is markedly reduced, treatment can be matched not only to pathology but also to physiological vulnerability. Sleep-targeted intervention may be initiated to improve consolidation and glymphatic function; a disease-modifying agent or RNA-based therapy may then be delivered using an optimized carrier or ultrasound-assisted approach; and serial biomarker testing can quantify whether the intervention is biologically active within weeks or months rather than years. This kind of pathway is no longer science fiction. Each individual component already exists in early clinical form.

The same logic can be extended beyond dementia. In glioblastoma, circulating vesicle signatures could help define tumor subtype and recurrence risk, while magnetic or lipid carriers improve the local delivery of therapeutic payloads across a partially heterogeneous barrier. In traumatic brain injury, acute GFAP and UCH-L1 may guide triage, neurofilament light chain may track ongoing axonal injury, and sleep-state disruption may identify patients at risk for persistent cognitive symptoms. In synucleinopathy, REM sleep behavior disorder can serve as an early physiological warning, blood-based injury markers can track progression, and brain-directed delivery systems may eventually enable targeted disease-modifying therapy before widespread neuronal loss occurs. Across these examples, the same organizing principle applies: early biology should guide both timing and method of intervention.

A further opportunity lies in computational integration. As datasets expand, machine-learning models will likely combine plasma analytes, electrophysiological features, wearable-derived sleep patterns, imaging measures, and treatment metadata to generate individualized response predictions. Such systems must be developed cautiously and transparently, but they could substantially improve the interpretation of biomarker trajectories and the scheduling of targeted delivery. Importantly, computational tools should remain subordinate to biological understanding. The goal is not to replace mechanism with correlation, but to use computation to manage complexity once the key mechanistic variables are known.

The field should also resist two common errors. The first is technological optimism without validation. Sensitive assays, elegant carriers, or sophisticated devices are not clinically useful unless they improve outcomes in representative populations. The second is reductionism. No single biomarker, sleep feature, or nanocarrier will solve the problem of brain disease in isolation. Real progress will come from disciplined combination, careful staging, and iterative trial design. That is why integrated review frameworks are useful: they shift the focus from isolated innovation toward coordinated translation.

For these reasons, the coming years should prioritize studies that link molecular, physiological, and engineering domains at patient scale. A mature neuroscience clinic of the future may look very different from the memory clinic or neuro-oncology service of the past. Routine blood draws may be interpreted alongside home sleep metrics; delivery procedures may be scheduled according to oscillatory physiology; and therapeutic effect may be inferred from rapid biological response rather than delayed clinical decline. If that vision is realized, neurological care will become earlier, more precise, and substantially more actionable than it is today.

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Agricultural Sciences

Modelling the Optimization of Irrigation Regimes for Agricultural Crops in Shida Kartli up to 2050

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Abstract

Research Relevance

Global climate change represents one of the most pressing challenges of the twenty-first century, exerting a substantial influence on both the agricultural sector and the management of water resources. Owing to its distinctive climatic characteristics, the Shida Kartli region is marked by a high degree of aridity and an increasing demand for irrigation water.

Objective

The primary objective of this study is to optimize irrigation regimes for agricultural crops across the municipalities of the region and to develop mathematical models for forecasting future irrigation requirements and related indicators up to the year 2050.

Methodology

The research involved a comprehensive assessment of climatic parameters within the administrative units of Shida Kartli, namely the municipalities of Gori, Kaspi, Kareli, and Khashuri, during the growing season (April–September). The calculations were based on the soil water balance approach, incorporating key variables such as air temperature, precipitation, relative humidity, and soil evapotranspiration coefficients.

Results

The findings reveal pronounced disparities between lowland and highland zones. The analysis demonstrated that during July and August the optimal irrigation interval decreases to approximately 16–17 days in Gardabani, Gori, and Khashuri, whereas in Kareli Municipality the corresponding interval reaches 31–33 days. Taking projected climate change scenarios into account, irrigation intervals in lowland areas are expected to decline even further by 2050, potentially resulting in significant water shortages and increasing pressure on regional water resources.

Conclusion

The study offers practical recommendations regarding regional agro-climatic zoning, the immediate implementation of water-efficient irrigation technologies, including drip and sprinkler irrigation systems, and the modernization of existing irrigation infrastructure. These measures are considered essential for enhancing water-use efficiency and ensuring the sustainable management of water resources under future climatic conditions.

Keywords: Shida Kartli, irrigation regime, irrigation scheduling, optimization, modelling, climate change, irrigation, water resource management.

Introduction

Global climate change is one of the most significant challenges of the twenty-first century, exerting a direct impact on both the agricultural sector and water resource management. Due to its geographical location and distinctive climatic characteristics, the Shida Kartli region is characterized by a high degree of aridity and a substantial demand for irrigation water [3].

As Shida Kartli represents one of Georgia's leading agricultural regions, climate-related risks are closely linked to the country's food security and economic stability. Projected increases in air temperature and the uneven distribution of precipitation by 2050 are expected to intensify existing challenges, highlighting the urgent need to reassess current irrigation practices and implement the principles of climate-smart agriculture [2].

The aim of this study is to analyse agro-climatic parameters across the municipalities of the region and, based on the obtained data, to model the optimization of irrigation regimes under future climate conditions. The findings of the research are expected to provide a practical foundation for the efficient management of water resources and the development of long-term adaptation strategies within the region [3].

Main Body

Within the framework of the study, the climatic characteristics of the four principal administrative units of the Shida Kartli region—Gori, Kaspi, Kareli, and Khashuri municipalities—were comprehensively analysed and quantified for the growing season (April–September).



Map 1 of Shida Kartli

To optimize irrigation regimes, an integrated methodological approach was employed, based on the following key parameters:

- Mean monthly air temperature (T , °C) and atmospheric precipitation (P , mm);
- Relative air humidity (r , %) and the influence of wind speed;
- Evapotranspiration coefficients (ET , m³/ha), reflecting water losses from both soil and plant surfaces.

The calculation of irrigation intervals and projected irrigation schedules was carried out through mathematical modelling. The model incorporates soil water balance components and their functional relationships, enabling a precise estimation of irrigation water requirements and the optimal frequency of irrigation events under changing climatic conditions [1,4].

The estimation of evaporation intensity from soil and vegetation surfaces, as well as projected irrigation water demand, is based on an exponential functional relationship expressed by the following equation:

$$E = E_0 * e^{-K * T} * \left(1 - \frac{r}{100}\right) * 10$$

where:

- E – evaporation intensity (irrigation water demand coefficient);
- E_0 – baseline evaporation coefficient;
- e – the base of the natural logarithm (mathematical constant, $e \approx 2.718$);
- K – empirical regional climatic adjustment coefficient;
- α – region-specific climatic coefficient;
- T – mean monthly air temperature (°C);
- r – relative air humidity (%).

Table 1. The climatic and agro-meteorological data for each municipality (T , °C)

Municipality	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Annual
Gori	0.2	2.1	6.5	14.78	20.27	24.75	28.56	27.55	22.85	14.17	7.3	2.0	14.2
Kareli	0.5	2.3	6.8	14.95	20.50	24.90	28.50	27.60	22.90	14.3	7.5	2.2	14.4
Khashuri	0.1	1.8	5.9	13.50	18.90	23.10	26.40	25.80	21.20	13.2	6.8	1.5	13.2
Kaspi	-1.5	-0.3	3.2	10.10	15.40	19.20	22.50	21.90	17.60	10.8	4.9	0.1	10.3

Table 2. Monthly and Annual Precipitation Amounts (P, mm) in the Municipalities of Shida Kartli

Municipality	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Annual
Gori	18	22	30	52	75	68	36	32	41	35	26	17	452
Kareli	19	23	32	55	78	70	37	31	43	36	27	18	469
Khashuri	21	25	35	62	86	79	44	38	48	42	31	20	532
Kaspi	25	30	44	75	108	98	58	52	61	53	38	24	716

Based on the implementation of the proposed exponential mathematical model and the processing of empirical data, projected estimates of irrigation water demand and irrigation intervals were obtained for all four municipalities of the Shida Kartli region during the

Table 3. Irrigation Scheduling and Climate Data for Shida Kartli Region

Gori Municipality									
Month	Air temperature T°C	Precipitation p (mm)	Relative humidity %	Wind (m/s)	Irrigation norm m (m³/ha) 500-825	recipitation fraction / Effective precipitation share 10μ P	Discharge / Flow rate e=α*t*(1-r/100)*10	Tirrigation interval / Irrigation period= (m+10μ P)/ e	დღ.
IV	12.65	49.01	67.0	0.86	500	123	41.75	14.92	15
V	17.56	59.60	69.4	0.78	500	149	42.99	15.10	15
VI	21.55	62.47	69.4	0.76	700	187	59.35	14.95	15
VII	24.85	47.03	68.5	0.78	825	118	62.62	15.06	15
VIII	24.40	41.68	67.4	0.76	825	146	63.64	15.26	15
IX	19.95	33.56	71.1	0.70	700	84	51.89	15.11	15
Kaspi Municipality									
IV	12.65	49.01	67.0	1.12	500	123	41.75	14.92	15
V	17.56	59.60	69.4	1.02	500	149	42.99	15.10	15
VI	21.55	62.47	69.4	0.98	700	187	59.35	14.95	15
VII	24.85	47.03	68.5	1.02	775	141	62.62	14.63	15
VIII	24.40	41.68	67.4	0.98	775	104	55.68	15.79	16
IX	19.95	33.56	71.1	0.91	700	84	51.89	15.11	15
Karaleti Municipality									
IV	12.31	49.01	68.5	0.86	500	123	42.65	14.61	15
V	17.44	59.60	70.1	0.78	500	209	46.93	15.11	15
VI	21.66	62.47	69.9	0.76	700	187	58.68	15.12	15
VII	25.19	47.03	68.1	0.76	825	141	64.28	15.03	15
VIII	24.97	41.68	67.6	0.78	825	146	64.72	15.00	15
IX	20.29	33.56	71	0.7	700	84	52.96	14.80	15

Xashuri Municipality									
IV	11.62	50.90	71.3	0.13	400	153	36.68	15.07	15
V	16.68	63.60	73.4	0.12	400	191	39.93	14.80	15
VI	20.59	71.80	74.4	0.11	600	215	52.71	15.46	15
VII	23.92	48.00	74.1	0.12	825	120	61.95	15.25	15
VIII	23.81	38.20	73.1	0.13	825	134	64.05	14.97	15
IX	19.09	38.60	75.1	0.11	600	97	47.53	14.66	15

growing season (April–September). The resulting quantitative data were systematically analysed, organized, and are presented below. These findings provide a scientific basis for evaluating irrigation requirements and support the development of optimized water management strategies under both current and anticipated climatic conditions.

Table 4. Forecasted Irrigation Parameters During the Growing Season (April–September)

Municipality	Parameter	IV	V	VI	VII	VIII	IX
Gori	Mean Monthly Temperature (T°C)	14.78	20.27	24.75	28.56	27.55	22.85
	Projected Water Demand (E)	57,72	65.31	78.21	73.00	79.26	74.03
	Irrigation Interval (days)	16	15	15	16	15	15
Karelli	Mean Monthly Temperature (T°C)	14.95	20.50	24.90	28.50	27.60	22.90
	Projected Water Demand (E)	61 34	69.21	81.04	76.43	85.17	78,50
	Irrigation Interval (days)	15	15	15	16	15	16
Khashuri	Mean Monthly Temperature (T°C)	13.50	18.90	23,10	26.40	25.80	21,20
	Projected Water Demand (E)	52.10	58.40	68.15	65.30	70.12	64.80
	Irrigation Interval (days)	17	16	15	16	15	16
Kaspi	Mean Monthly Temperature (T°C)	10,10	15.40	19.20	22.50	21.90	17.60
	Projected Water Demand (E)	38,45	44.20	51.30	49.80	53.40	48.20
	Irrigation Interval (days)	23	20	18	19	17	19

The analysis of the obtained results reveals a pronounced climatic and hydrological contrast between the lowland and upland zones of the region.

Gori and Kareli Municipalities:

The study demonstrates that during the peak phase of the growing season (July–August), when the mean monthly air temperature reaches its maximum values (27.55°C–28.56°C), the projected evapotranspiration intensity (E) attains its highest level, ranging from 79.26 to 85.17 units. Such intensive moisture loss leads to a deficit in the soil water balance, resulting in a reduction of the optimal irrigation interval to a minimum of 15–16 days. This indicates a high level of climatic stress and increased irrigation demand in the lowland areas.

Kaspi Municipality:

A markedly different pattern is observed in the upland zone. Due to higher relative humidity (77.7%–79.9%) and a comparatively lower thermal regime, the minimum projected water demand in April is recorded at 10.96, which extends the irrigation interval to a maximum of 53 days. During the active summer period, however, the irrigation interval stabilizes at approximately 21–22 days. This reflects more favorable moisture conditions and reduced evapotranspiration pressure compared to lowland municipalities.

Khashuri and Gori Municipalities:

These administrative units exhibit transitional agro-climatic characteristics. Their irrigation intervals during the summer months are optimized within the range of 15–17 days, reflecting intermediate climatic conditions between lowland and upland zones.

Overall, the findings confirm that spatial variability in climatic parameters significantly influences irrigation requirements, necessitating differentiated, location-specific water management strategies across the region [4,5,6,7].

Conclusion

The mathematical modelling conducted in this study confirms that traditional, fixed calendrical irrigation schedules are not capable of ensuring the rational and efficient management of water resources under conditions of climate variability.

The developed exponential model enables dynamic adjustment of irrigation norms and schedules based on real-time values of air temperature (T) and relative humidity (r). This adaptive approach provides a more accurate representation of crop water requirements and supports improved decision-making in irrigation management.

In zones characterized by high evapotranspiration rates (Marneuli, Gardabani), the implementation of modern water-saving irrigation technologies, particularly drip irrigation systems, is essential for reducing water losses and improving overall water-use efficiency.

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Historical Sciences

CHANGES IMPLEMENTED REGARDING THE ORGANIZATION OF PEDAGOGICAL INTERNSHIPS AT AZERBAIJAN STATE PEDAGOGICAL UNIVERSITY

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ABSTRACT

Various factors shape distinct civilizations. These factors are numerous and possess diverse characteristics. In this context, the development of education and the educational system – which plays a crucial role in societal progress – is of great interest. Education, being both a leading and a conservative component of culture, is evaluated based on qualitative indicators alongside quantitative ones. Therefore, it is no coincidence that education is viewed as a repository of values – such as knowledge, skills, competencies, and abilities – accumulated over millennia. A primary objective of the educational process, particularly in pedagogical universities, is to train the professionals who will educate future generations. Through this process, students acquire new knowledge and develop into qualified specialists across various fields. To this end, they learn to apply the knowledge they have acquired through a pedagogical internship. This internship consists of three months at the university and one month at a school. Unlike in previous years, the core requirements and documentation procedures for the internship have been revised, time – consuming inefficiencies eliminated, school placement rules relaxed, and the final defense requirement abolished.

Keywords: pedagogical experience, innovation, education, report, moral values, theoretical knowledge, practical perspective

Introduction

Azerbaijan State Pedagogical University (ASPU) is one of the universities in Azerbaijan and possesses its own distinctive traditions. Since its inception, the institution has maintained strong traditions, and renowned educators from across the republic have played a vital role there in nurturing the new generation. With a history spanning 105 years, the University was established through the perseverance, dedication, and self – sacrifice of Azerbaijan intellectuals; it has traversed a complex yet honorable path and contributed to the development of national consciousness. The university is renowned as an educational and scientific institution that places special emphasis on the training of pedagogical and academic – pedagogical personnel. These traditions have been upheld for many years and continue to this day. It is no coincidence that “Committed to tradition, open to innovation” is the Pedagogical University’s core motto.

1. The importance of organizing pedagogical practice

Pedagogical internship – or practical training – is considered the most crucial stage in the preparation and professional development of future teachers. It is precisely during this period that

theoretical knowledge acquired at the university is applied and tested within the school environment.

Key aspects highlighted during the teaching practicum include linking theory with practice, developing teaching skills, classroom management, boosting self – confidence, familiarization with the professional environment, self – assessment and analysis, and so forth. In this process, theoretical knowledge regarding teaching methods and pedagogy is directly applied during classroom interactions with students, thereby bridging theory and practice. At the Pedagogical University, this process begins with student – teachers practicing on their own classmates; subsequently, those who have gained experience are sent to schools.

The process of conducting lessons fosters skills such as lesson planning, effective time allocation, the proper use of teaching resources, and assessment. Classroom management involves gaining experience in capturing students' attention, establishing and maintaining discipline, and communicating with students of diverse temperaments. For student teachers, the boost in self – confidence gained from applying acquired knowledge in the classroom can be considered a key criterion. Students undergoing short – term teaching practicums at schools attach great importance to familiarizing themselves with the professional environment. The proper organization and management of relationships – involving the school administration and staff, subject teachers, and the parents of students in their assigned classes – are examined from a practical perspective. Against this backdrop, students identify their strengths and weaknesses, understand the areas requiring personal development, and lay the foundation for their future professional activities through self – assessment and analysis. The pedagogical internship facilitates the transformation of the student – intern into a professional teacher ready for the actual teaching process.

2. New regulations regarding the conduct of pedagogical internships at ASPU

Azerbaijan State Pedagogical University distinguishes itself through its extensive experience in organizing pedagogical internships. Committed to its heritage and upholding traditions established over many years, the University has developed a system capable of meeting the needs of today's students. In this context, the adoption and practical implementation of the new regulations regarding student internships in their respective fields are of particular interest. This process was conducted in accordance with the Regulation approved by the Resolution of the Cabinet of Ministers of the Republic of Azerbaijan dated December 30, 2023 [12] [10]. The organization of internships based on new regulations for specific fields of study at ASPU began in 2025. The regulations apply to the University, its branches, and its affiliated college across all higher and secondary specialized education levels. Particular emphasis is placed on the primary objectives and types of internships within the regulations.

The primary objectives of the internship include consolidating the theoretical knowledge acquired by the student, complementing it with practical skills and competencies, preparing the student for effective professional activity, and familiarizing them – depending on their field of specialization – with new technologies, modern production sectors, work methods, and other relevant aspects. It is also important to include the development of the student's capacity for innovative learning and competence building in this context [10].

In accordance with the regulations, the following have been established as the primary types of internships at the University: instructional, industrial, pre – graduation, scientific – pedagogical, and scientific – research internships. Separate internship programs have been developed for the various types of internships associated with the specialization in the curriculum.

The list of enterprises (organizations) where students would undertake their internships was determined four months prior to the start of the internship, adhering to the principle of subordination. The students' field – specific internships were organized during the spring semester,

spanning the months of February to May. The internship timeframe was aligned with the academic calendar of the relevant academic year. Each student intern prepared a report regarding the internship undertaken during May and June. Under the new regulations, it was stipulated that these reports – along with other documentation – be submitted to the Internship Commission and that defence sessions be organized; however, the defense sessions for student interns were cancelled for 2026.

Key requirements for organizing pedagogical internships include ensuring the internship site aligns with the student's specialization, establishing conditions that are safe and harmless to life and health, and creating a continuous link between teaching – learning and the internship itself. At the same time, requirements established for the organization of the internship include ensuring the student's participation in creative and research activities, enhancing skills in the application of modern information technologies, and familiarizing the student with modern technologies, work methods, and other innovations [12].

The student's professional work in their field of study during their academic tenure was recognized as an internship by the Internship Commission – established by the educational institution in accordance with the aforementioned Regulation and based on the department's recommendation. In this context, each week of work activity was equated to 1.5 credits. The duration of the internship involved a minimum of 20 hours per week, based on a five – day work schedule.

According to the regulations, the University requires the preparation of an internship report form for the student. The report must be prepared in accordance with the requirements of the internship program and should outline the content of the internship, the analyses conducted, and the conclusions reached [10].

Students were required to submit their internship report in Microsoft Word format and deliver their presentation to the commission using PowerPoint, in the language of their instruction. Although student interns prepared reports at the end of the internship this year (2026), they were not required to give presentations due to the cancellation of the defense sessions. The preparation of the report was based on information regarding the pedagogical internship conducted at both the university and the school. First, the location and timing of the internship are specified; details regarding the university and the host school – including their addresses and information about the school (such as the number of teaching and administrative staff and the total number of students) – are confirmed, along with the university – based methodologists and supervising teachers. Subsequently, information was provided regarding the organization and conduct of trial lessons – including the schedule (dates, classes, and topics) – as well as details about the specific classes and learners involved (covering students' general knowledge, interests, and cognitive levels; visual and auditory learning skills; the formation and development of various types of intelligence; the presence of students with special needs, etc.). The next point addressed the readiness of the classroom for instructional activities. In this context, consideration must be given to ensuring that the classroom's material – technical infrastructure and sanitary – hygienic conditions support the effective organization of the teaching and learning process; that lighting and ventilation systems comply with relevant standards; and that the environment fosters healthy and comfortable student activity. The equipping of classrooms with projectors, computers, and interactive whiteboards – essential in the era of modern educational technologies – was noted in all of this year's student reports. These technical capabilities have facilitated the effective presentation of electronic learning resources and presentation materials. Another issue highlighted in the students' reports concerned the creation of a favorable psychological environment in the classroom, enabling learners to freely express their ideas and opinions. Fostering mutual respect, cooperation, and constructive communication among students – and ensuring they feel at ease sharing their ideas

and views – is a key factor in positively influencing the development of their self – confidence and socio – communicative skills.

In their reports, the student interns provided information on the outlines and lesson plans for their specialized subjects (history and geography), specified the topics, and included the full texts of six lesson plans used during the organization of the lessons.

The reports include a section dedicated to the individual analysis of observed lessons and reflections on their discussion. In this section, student interns analyzed the lessons they attended and observed during their internship. They noted that the observed lessons were organized in a student – centered and interactive manner, in accordance with modern teaching principles. Throughout the lessons, active teaching methods – such as clustering, role – playing, crosswords, Venn diagrams, and question – and – answer sessions – were employed purposefully and effectively, tailored to the content of the topics. Student observations highlight the effective planning and management of lesson time, as well as the high level of organization regarding active student participation in the learning process and their involvement in group work. Furthermore, the analysis and methodological discussion of demonstration lessons conducted during the internship period acknowledged the proper alignment of lesson objectives and tasks with educational standards, as well as the creation of an engaging and purposeful motivation phase. The alignment of selected teaching methods and forms with the students' age characteristics and knowledge levels, along with the precise and concrete definition of assessment criteria, has positively influenced the professional practice of the student teachers.

The reports include photographs documenting the organization of sample or trial lessons, as well as the methodological and digital resources created during the teaching practicum. The visual aids developed presented the core content of the topics in a systematic and visual manner, effectively capturing the students' attention.

The reports specify the key competencies (knowledge, skills, habits, values, qualities, and proficiencies) developed during the teaching process.

The student teachers included transcripts of discussions held with learners on moral and ethical topics in their reports. In this regard, the main themes of these educational discussions were: "Karabakh is Azerbaijan!" (F.Mammadli), "Moral Values" (T.Mammadli), "A Good Friend is a Treasure" (J.Mammadova), "Language is a People's Great Wealth and Asset" (A.Mammadzada), "Discipline and Responsibility" (A.Nuriyeva), "On Upbringing" (Z.Gadirova), "Children and War" (F.Rajabov), "What is Happiness?" (F.Khalilov), "Nature Wants to Live" (J.Khalilov), "My Life Ideal" (S.Khuduyeva), and "Who is a True Human Being?" (A.Yusubov).

A separate section in the interns' reports is dedicated to evaluating the activities undertaken from scientific, methodological, pedagogical, and psychological perspectives.

During the internship period, groups of 10 – 15 students were formed; four sample lessons were conducted during the teaching internship, and two trial lessons were held during the practical training.

The teaching workload related to internships at the university is regulated by the "Rules for Conducting Field – Specific Internships for Students of Higher and Secondary Specialized Education Institutions", approved by Decision No.489 of the Cabinet of Ministers of the Republic of Azerbaijan dated December 30, 2023; the "Teaching Workload Norms for Academic Staff", approved by Decision No. KQ – 12 of the Board of the Ministry of Science and Education of the Republic of Azerbaijan dated September 3, 2024; and the aforementioned regulation.

For university – based internships – including the review and acceptance of reports – an allocation of 5 – 10 hours per group per working week has been established; for the supervision of industrial and pre – graduation internships – including report review and acceptance – the allocation is 3 – 5 hours per group per working week.

The key internship documents include: sample lessons conducted during the teaching internship and their objectives (App.1); the evaluation form for students' internship lessons (sample and trial) (App.2); the procedure for preparing the internship report (presentation) and the feedback form (App.3); the Internship Commission's final evaluation table (App.4); the Internship Commission member's evaluation sheet (App.5); the internship program (App.6); the internship logbook (App.7); and the sample agreement with the internship site (App.8) [10].

The precise allocation of the teaching workload for internships across various specializations was formalized by the rector's order regarding the distribution of the teaching workload for the new academic year. The assessment of internship outcomes was to be conducted by internship commissions – established by the educational institution and comprising internship supervisors appointed by both the institution and the internship host organization – based on assessment criteria defined by the educational institution. Assessment procedures were established separately for each type of internship.

Of the 30 credits allocated for internships within the university's undergraduate degree programs, 15 credits (10 weeks) are designated for academic internship, 7.5 credits (5 weeks) for industrial (pedagogical) internship, and the remaining 7.5 credits for the preparation, review, and acceptance of the internship report by the specialized internship commission. It should be noted that this academic year, the specified allocation was modified, and work of the commission was discontinued.

The assessment of the teaching and pedagogical internship was conducted by the internship supervisor (instructor) using the "Form 2" evaluation form [App.1]. This form served as a key document for evaluating the intern's knowledge during the internship period, enabling a more accurate assessment of the student's knowledge, skills, competencies, abilities, and other attributes.

Form 2



Azerbaijan State Pedagogical University Students' practical (sample and test) lessons Evaluation form

Intern student:		Photo
Student's Personal No.:		
Faculty:		
Specialization:		
Head of practice:		
Practice base school:		
Internship start date:	Internship end date:	
Explanation of the abbreviations in front of the items in this assessment form: (C): It has weaknesses, (B): Acceptable, (A): It's good. Mark the appropriate option with a (+).		

			C	B	A
1	SPECIALIZATION AND VOCATIONAL EDUCATION				
1.1	SPECIALIZED SKILLS				
	1.1.1.	Knowledge of basic principles and concepts related to the topic			
	1.1.2.	Connecting the main principles and concepts covered in the topic in a logical framework			
	1.1.3.	Use oral speech and visual aids (pictures, diagrams, graphs, formulas, etc.) appropriately as required by the topic			
	1.1.4.	Ability to relate the topic to other topics in the field			
1.2	VOCATIONAL EDUCATION				
	1.2.1.	Knowledge of special education approaches, methods and techniques			
	1.2.2.	Ability to use educational technologies			
	1.2.3.	Being able to identify misdeveloped concepts in students			
	1.2.4.	Inability to provide appropriate and sufficient answers to student questions			
	1.2.5.	Ability to ensure the safety of the learning environment			
2	TEACHING AND EDUCATIONAL PROCESS				
2.1	PLANNING				
	2.1.1.	Ability to write a lesson plan in a clear, understandable and systematic manner			
	2.1.2.	Being able to clearly express goals and target behaviors			
	2.1.3.	Ability to identify target behaviors using appropriate methods and techniques			
	2.1.4.	Be able to select and prepare appropriate equipment and materials			
	2.1.5.	Being able to identify assessment forms appropriate to target behaviors			
	2.1.6.	Ability to connect the topic with previous and subsequent lessons			
2.2	TEACHING PROCESS				
	2.2.1.	Ability to use various teaching methods and techniques appropriately			
	2.2.2.	Inability to use time effectively			
	2.2.3.	Ability to organize educational games to increase pupil activity			
	2.2.4.	Ability to continue the training process based on individual differences			
	2.2.5.	Ability to use teaching equipment and materials appropriately at the grade level			
	2.2.6.	Ability to generalize and make appropriate recommendations			
	2.2.7.	Inability to relate the topic to real life			
	2.2.8.	Ability to assess the level of achievement of target behaviors			
2.3	CLASS MANAGEMENT				
	When the class starts				
	2.3.1.	Not being able to make an appropriate introduction to the lesson			
	2.3.2.	Inability to attract interest and attention to the lesson			
	Lesson process				
	2.3.3.	Ability to create a democratic learning environment			
	2.3.4.	Ability to maintain interest and motivation in the lesson			
	2.3.5.	Inability to take appropriate measures against interference and disruptions in the lesson			
	2.3.6.	Ability to use tool without encouragement or punishment			
	At the end of the lesson				
	2.3.7.	Being able to summarize and conclude the lesson			
	2.3.8.	Being able to provide information and assignments related to the next lesson			
	2.3.9.	Ability to prepare pupils to leave the classroom			

2.4	COMMUNICATION			
2.4.1.	Ability to communicate effectively with pupils			
2.4.2.	Ability to give understandable explanations and instructions			
2.4.3.	Being able to ask thought – provoking questions about the topic			
2.4.4.	Ability to use voice tempo effectively			
2.4.5.	Being able to listen to pupils with interest			
2.4.6.	Ability to use oral speech and body language effectively			
3	EVALUATION AND REGISTRATION			
3.1.	Ability to prepare appropriate assessment materials			
3.2.	Providing feedback appropriate to students' levels of understanding			
3.3.	Assessing students' results (answers) in a short time and reporting to relevant persons			
3.4.	Record assessment results			
4	OTHER PROFESSIONAL SKILLS			
4.1.	Know the laws and regulations related to the profession			
4.2.	Be open to professional feedback, suggestions and criticism			
4.3.	Being able to participate and contribute to school events			
4.4.	To be an example to others with personal and professional behavior			
5	CONTINUITY			
	TOTAL			

App. 1. Form 2

According to the regulations, a student who fails to successfully complete any type of internship is given the opportunity to retake that specific internship in the following academic year upon payment of the corresponding credit fee. To undertake the industrial (or pedagogical) internship, the student must have successfully completed the academic internship and must not have exceeded the attendance limit. A student who successfully completes both internships is considered to have concluded the internship process upon submission of the report.

The following normative and legal documents of the Republic of Azerbaijan can be cited as primary sources used by the university administration, the methodologists and others involved in the internship process, and the student interns themselves during the drafting of the regulations and the implementation of their key provisions (Form 9):

- ✓ Constitution of the Republic of Azerbaijan [2];
- ✓ Labor Code of the Republic of Azerbaijan [5];
- ✓ State Strategy and Action Plan for the Development of Education in the Republic of Azerbaijan [16];
- ✓ Law of the Republic of Azerbaijan on Education [6];
- ✓ Law of the Republic of Azerbaijan on General Education [7];
- ✓ Assessment Concept in the general education system of the Republic of Azerbaijan [1];
- ✓ State standards of general education in the Republic of Azerbaijan [15];
- ✓ Ethical Code of Conduct for Educators [3];
- ✓ Samples of state documents on education and the Rules for their issuance [13];
- ✓ Standards for the material – technical base and educational infrastructure of the educational institution [14];

- ✓ Rules for organizing formal education [11] and etc.

3. Key participants in the pedagogical internship



Image 1. Methodologist Assoc.Prof.Ayten Mehdiyeva and students of group TCM2101B

Operating on the basis of the new Regulations and the documents reflected therein, I, Mehdiyeva Ayten Ali, have always endeavored – in my capacity as a methodologist – to structure my work in the right direction, in accordance with the demands of the times [Image 1].

To this end, alongside reviewing the documentation, I have maintained constant contact with the student interns and sought to understand their perspectives. In this regard, data gathered from several surveys conducted with them proved invaluable in structuring my work. First and foremost, I would like to note that this year³ students achieved superior results compared to those from previous years. The selected topics include “Effective Communication Tools” (A.Yusufov), “Classroom Communication Issues” (F.Mammadli), “At – Risk Groups” (F.Khalilov), “The Teacher³ Role in Adapting Students to the Educational Environment” (A.Nuriyeva), “Resolving Conflict Situations with Students” (T.Mammadli), “Fostering Students Motivation” (J.Khalilov), “Student – Centered Education” (F.Rajabov), “Stress Management and Emotional Intelligence” (S.Khuduyeva), and “Teacher – Parent Cooperation” (Z.Gadirova). Two of the topics presented for discussion among the student interns generated particular interest and were discussed extensively. Among these, the topics “Artificial Intelligence and the Traditional Teacher” (J.Mammadova) and “The Impact of Social Networks on Students” (A.Mammadova) sparked great interest among the students, leading to an extensive exchange of views. This interest was driven, in part, by the changes taking place in Azerbaijan – specifically the approval of the “Artificial Intelligence Strategy of the Republic of Azerbaijan for 2025 – 2028”, which aims to accelerate the development of artificial intelligence in the country and enhance information technologies and their management mechanisms in this field [9]. On this basis, plans are in place to develop national language models in Azerbaijan and launch the Edu SLM artificial intelligence mentor for schoolchildren by the end of 2028 [8]. At the same time, the innovations introduced and implemented at the University are attracting students’⁴ attention. Activities carried out at ASPU in the fields of media and digital communication during the first six months of 2026 have generated significant interest. The Public Relations and Marketing Department has disseminated information regarding new developments, projects, and events concerning the University³ academic, scientific, international, and social life through the official website, social media accounts, and other communication channels. Posts and videos published on ASPU³ official Facebook, Instagram, and YouTube accounts, as well as on the ASPU TV platform, garnered nearly 20 million views during the first six months of 2026. These results further confirm the continued expansion of the university³ digital communication capabilities [4].

Conclusion

Thus, the organization of the pedagogical internship was carried out professionally by the leadership of both the higher education institution and the general education school, and the necessary material – technical and methodological conditions were ensured for the effective organization of the students' practical activities. The measures implemented in this regard were aimed at accelerating the students' adaptation to the real teaching environment and creating the conditions for them to embark on their professional careers well – prepared.

The successful implementation – by both teachers and students – of the new type of internship process, which began in February 2025, can be considered a significant achievement in the academic life of the Azerbaijan State Pedagogical University. This process will undergo further refinement in the coming years, paving the way for the internship program to become truly exemplary. Implementing innovations in this area requires wisdom, composure, and patience; the measures taken by our university in this regard are highly commendable.

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MATHEMATICAL CORRECTNESS OF THE AUTHENTICATION PROCESS BASED ON A FINITE-STATE MACHINE

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Annotation

This paper examines a mathematical model of multifactor authentication in which the factor verification sequence is controlled by a deterministic finite automaton. The baseline scenario is a two-factor "biometric verification → PIN code" scheme, supplemented by a reset or session end event. A state set, an input alphabet, a transition function, and initial and accepting states are formally defined. Based on this, the determinism of the automaton, the reachability of the accepting state, the absence of deadlocks, and the impossibility of successfully completing a minimal session if the established factor order is violated are proven. To analyze the automaton's trajectories, a probabilistic description of state visit frequencies and normalized Shannon entropy are introduced, allowing for a quantitative characterization of the uniformity of the transition distribution. It is shown that the normalized entropy lies between 0 and 1 and reaches a maximum for a uniform state probability distribution. Additionally, the session success rate, the wireless channel stability indicator, and the integral stability metric are considered. The boundedness of the integral metric is proven on the interval from 0 to 1 for non-negative weights whose sum is equal to one. It is shown that a finite-state machine can be used as a formal mechanism for accessing session keys without replacing them with cryptographic primitives. The proposed model is designed for mobile and embedded systems with limited computing resources.

Keywords: authentication, deterministic finite automaton, DFA, multifactor authentication, biometrics, PIN code, Shannon entropy, formal verification, ChaCha 20- Poly 1305, session key.

1. Introduction

Modern authentication systems increasingly combine several independent factors: biometrics, PIN codes, hardware tokens, and confirmations from a trusted device. The security of the procedure is determined not only by the strength of each individual factor, but also by the correctness of the logic behind their sequential application. If the system allows for the transition to the next stage without completing the previous one, the reuse of an intermediate state, or an

incorrect return after an error, then formally strong authentication mechanisms can be combined into a logically vulnerable protocol.

One natural way to describe such logic is as a deterministic finite automaton. A finite automaton defines a finite set of states and a unique transition function between them. This allows the authentication process to be represented not as a set of disparate conditions in program code, but as a formal system whose properties can be proven. Classical finite automaton theory provides a framework for analyzing reachability, determinism, termination, and transition structure [1, 2].

For practical systems, the boundary between control logic and cryptographic security is particularly important. A DFA should not be considered an independent cryptographic primitive. Its purpose is to permit or deny the transition to a secure session depending on the correctness of a sequence of factors. Once an accepting state is reached, a session cryptographic context is formed, and data confidentiality and integrity are ensured by specialized algorithms, such as the ChaCha 20- Poly 1305 AEAD scheme [3]. This approach is consistent with the general principle of separation of concerns: the state machine is responsible for protocol state control, and cryptographic mechanisms are responsible for protecting data and key material.

DFA- based authentication process . To achieve this goal, the following tasks are solved: formalizing two-factor authentication "biometrics $\rightarrow$ PIN "; defining a complete transition function with secure return; studying the automaton graph; proving determinism, reachability, and the absence of deadlock states; introducing an entropy characteristic of the state trajectory; formalizing an integral stability metric; and describing the relationship between the receiving state and the formation of the session key.

2. Materials and methods

This paper utilizes a mathematical-theoretical approach that combines the theory of finite automata, graph theory, and information entropy. The design under study is a two-factor "biometrics $\rightarrow$ PIN " scheme controlled by a deterministic finite automaton. State visit rates, normalized Shannon entropy, authentication success rate, and normalized wireless channel stability are used to quantitatively evaluate the system's behavior. The cryptographic portion of the model is considered separately from the DFA logic: the accepting state of the automaton is used as a condition for admitting the session key and initiating AEAD protection.

The authentication process is represented by a deterministic finite state machine

$$A = (Q, \Sigma, \delta, q_0, F), \quad (1)$$

where Q is a finite set of states; Σ is the input alphabet; $\delta: Q \times \Sigma \rightarrow Q$ is the transition function; $q_0 \in Q$ is the initial state; $F \subseteq Q$ is the set of accepting states.

For a two-factor scheme, we set

$$Q = \{q_0, q_1, q_2\}, \quad F = \{q_2\}, \quad (2)$$

where q_0 corresponds to the initial secure state, q_1 – the state after successful confirmation of the biometric factor, and q_2 – the state of completed authentication.

We define the input alphabet as

$$\Sigma = \{b, p, r\}, \quad (3)$$

where b denotes successful completion of biometric verification, p – successful confirmation of the PIN code, and r – reset, refusal or termination of the current session.

The two-factor structure corresponds to a practical scenario in which biometric verification can be performed by the mobile platform's system mechanism, and then the user confirms the knowledge factor. Modern Android API BiometricPrompt provides a system interface for biometric authentication and supports various biometric modalities [4]. In this paper, the specific software implementation does not affect the mathematical properties of the automaton: only the event of successful or unsuccessful completion of the corresponding stage is significant for the model.

Allowed transitions are given by the expressions

$$\delta(q_0, b) = q_1, \quad \delta(q_1, p) = q_2, \quad \delta(q_2, r) = q_0. \quad (4)$$

For any state – input symbol pair not allowed by the protocol, a safe return to the initial state is introduced:

$$\delta(q_i, \sigma) = q_0, \quad \text{if } (q_i, \sigma) \text{ is not an allowed transition.} \quad (5)$$

Thus, the function δ is defined for all elements of the Cartesian product $Q \times \Sigma$. This is crucial: the software implementation must not contain undefined branches that could leave the system in an intermediate state.

Table 1. DFA transition function

Current status	b - biometrics	p - PIN	r - reset
q_0	q_1	q_0	q_0
q_1	q_0	q_2	q_0
q_2	q_0	q_0	q_0

The main correct authentication route is as follows

$$q_0 \xrightarrow{b} q_1 \xrightarrow{p} q_2. \quad (6)$$

After the end of a secure session or upon an explicit reset, a transition is performed

$$q_2 \xrightarrow{r} q_0. \quad (7)$$

The advantage of this scheme is that the order of the factors becomes a property of the automaton, rather than an informal agreement between individual functions of the program code.

To analyze the behavior of the machine across multiple sessions, we introduce a counter for each state's visits. Let be $N_i(T)$ the number of times the machine enters a state q_i per T registered transition. Then, the empirical probability of visiting a state is defined as

$$p_i = \frac{N_i(T)}{T}, \quad i = 1, \dots, n, \quad (8)$$

moreover

$$p_i \geq 0, \quad \sum_{i=1}^n p_i = 1. \quad (9)$$

For the base model $n = |Q| = 3$.

We define the entropy of the distribution of state visits according to Shannon [5, 6]:

$$H(Q) = - \sum_{i=1}^n p_i \log_2 p_i, \quad (10)$$

where the standard agreement is adopted $0 \log 0 = 0$.

The maximum entropy for n states is

$$H_{max} = \log_2 n. \quad (11)$$

the normalized entropy coefficient of the DFA trajectory as

$$D_{EC} = \frac{H(Q)}{\log_2 n}. \quad (12)$$

The coefficient D_{EC} is not a measure of cryptographic strength. It only characterizes the distribution of state visits: a low value indicates a concentration of the trajectory in a small number of states, while a value close to one indicates a more uniform distribution.

For a small number of observations, the empirical entropy may be statistically biased. Therefore, in practical estimation, D_{EC} it is advisable to either increase the sample size or apply known statistical corrections to the entropy estimate. Arbitrarily assigning values outside the range $[0,1]$ would contradict the definition of the normalized coefficient (12).

Let be S the number of sessions that terminated in the accepting state, and N be the total number of attempts. The success rate is defined as

$$C = \begin{cases} \frac{S}{N}, & N > 0, \\ 0, & N = 0. \end{cases} \quad (13)$$

Obviously,

$$0 \leq C \leq 1. \quad (14)$$

This metric reflects the operational stability of the procedure, but by itself does not distinguish between failure causes: incorrect PIN, biometric error, communication failure, or timeout. Therefore, for diagnostic purposes, it should be used in conjunction with the DFA transition log.

For systems in which part of the protocol is executed via Bluetooth, channel stability can be assessed by sampling RSSI values. $r_1, \dots, r_m$. The mean and standard deviation are given by the expressions

$$\mu = \frac{1}{m} \sum_{j=1}^m r_j, \quad \sigma = \sqrt{\frac{1}{m} \sum_{j=1}^m (r_j - \mu)^2}. \quad (15)$$

The initial stability index can be written as $1 - \sigma/|\mu|$. However, without additional normalization, it can take negative values with large variance. Therefore, to ensure the mathematical consistency of the integral model, we introduce a normalized form

$$BSSS = \max \left\{ 0, \min \left\{ 1, 1 - \frac{\sigma}{|\mu| + \varepsilon} \right\} \right\}, \quad \varepsilon > 0, \quad (16)$$

where the small value ε prevents division by zero. By definition,

$$0 \leq BSSS \leq 1. \quad (17)$$

To jointly evaluate the transition logic, channel state and session success, we define an integral metric

$$IMSI = w_1 D_{EC} + w_2 BSSS + w_3 C, \quad (18)$$

where

$$w_i \geq 0, \quad w_1 + w_2 + w_3 = 1. \quad (19)$$

The basic version can use weights $w_1 = 0,4$, $w_2 = 0,3$, $w_3 = 0,3$. Their choice is a model parameter and should depend on the system's purpose. The IMSI designation is used in this paper only for the integral stability metric and does not refer to the international mobile subscriber identity.

Achievement q_2 should be interpreted as logical permission to establish a secure session. The internal parameters of the cryptographic algorithm should not depend on arbitrary transitions of the automaton. One possible way to associate successful authentication with a session key is to calculate

$$K_{session} = H(K_{master} \parallel ID \parallel t \parallel S_{final}), \quad (20)$$

where K_{master} – master key; ID – device identifier; t – time or other unique parameter; S_{final} – representation of a successful final state; H – cryptographic hash function; $\parallel$ – concatenation.

For practical implementation, the function H must be a standard cryptographic function, not a home-made transformation. SHA-3, standardized by NIST in FIPS 202 [7], can be used as a normative example of a family of hash functions. The specific key derivation method must take into account the requirements of the chosen protocol and not be reduced to a simple concatenation of secrets without domain separation and parameter uniqueness verification.

Once the session key is generated, secure data transmission can be represented by a general AEAD operation

$$Enc(K_{session}, N, A, P) \rightarrow (C, T), \quad (21)$$

where N is a unique nonce, A is additional authenticated data, P is plaintext, C is ciphertext, T is the authenticity tag. RFC 8439 describes the use of ChaCha 20 in conjunction with Poly 1305 to ensure data confidentiality and authenticity [8].

Crucially, the DFA does not modify ChaCha20-Poly1305 or create its own encryption algorithm. The state machine only determines when a cryptographic session can be authorized. This separation reduces the risk of logical confusion between authentication and encryption.

3. Results

A formal analysis of the proposed model allowed us to establish properties that directly characterize the correctness of the authentication logic: deterministic transitions, reachability of the accepting state, adherence to a specified factor order, absence of deadlocks, and

boundedness of the normalized entropy and integral stability metric. The main results are presented below as theorems, corollaries, and proofs.

For a sequence of input symbols, an extended transition function is used $\delta^*: Q \times \Sigma^* \rightarrow Q$, defined recursively:

$$\delta^*(q, \varepsilon) = q, \quad \delta^*(q, x\sigma) = \delta(\delta^*(q, x), \sigma), \quad (22)$$

where ε is an empty string, $x \in \Sigma^*$, $\sigma \in \Sigma$.

Theorem 1. The automaton (1)-(5) is deterministic, its accepting state q_2 is reachable, and the minimal correct sequence of factors bp leads to successful authentication in two transitions.

Proof. By the definition of a deterministic automaton, for each pair $(q, \sigma) \in Q \times \Sigma$ the transition function must define at most one next state. In model (4)-(5), for each such pair, exactly one value is defined:

$$\forall q \in Q \forall \sigma \in \Sigma \exists! \tilde{q} \in Q: \delta(q, \sigma) = \tilde{q}. \quad (23)$$

Therefore, the automaton is deterministic.

For the sequence $w = bp$ we have

$$\delta^*(q_0, bp) = \delta(\delta(q_0, b), p) = \delta(q_1, p) = q_2. \quad (24)$$

Since $q_2 \in F$, the sequence bp is accepted by the automaton. The number of transitions is two, therefore, the accepting state is reached in a finite number of steps. The theorem is proven.

In a minimal authentication session, the fundamental condition is the order "biometrics $\rightarrow$ PIN". Let's consider the reverse sequence pb . The first character p arrives in the state q_0 and is not an allowed transition, so

$$\delta(q_0, p) = q_0. \quad (25)$$

After the next symbol b the machine goes into the state only q_1 :

$$\delta^*(q_0, pb) = \delta(q_0, b) = q_1. \quad (26)$$

Since $q_1 \notin F$, the reverse sequence of factors does not result in successful authentication. Similarly, skipping a biometric step, re-entering a biometric event in the state q_1 , or arbitrarily continuing after reaching [] q_2 causes a secure fallback q_0 in accordance with (5).

In terms of protocol security, this means that the accepting state cannot be reached by a single factor. The system allows the transition to q_2 only after the current state has become q_1 , and this state, in turn, is reached from q_0 only by the event b .

The automaton can be represented as a directed labeled graph

$$G = (V, E), \quad V = Q, \quad (27)$$

where an edge $(q_i, q_j) \in E$ exists if there is a symbol $\sigma \in \Sigma$ for which $\delta(q_i, \sigma) = q_j$.

A dead-end state is one from which no valid transition is defined. In the full model (4)-(5), the transition function is defined for each input symbol, so for any $q_i \in Q$

$$d_{out}(q_i) \geq 1. \quad (28)$$

Moreover, the main loop of allowed states contains a route

$$q_0 \rightarrow q_1 \rightarrow q_2 \rightarrow q_0. \quad (29)$$

Therefore, every state is reachable from q_0 , and from every state there is a path back to the safe region of the automaton. This prevents the protocol from getting stuck in a state that does not allow further event processing.

Corollary 1. With a complete transition function and safe return to q_0 DFA contains no undefined protocol states. Any input results in either permitted progression through the authentication chain or controlled reset.

Correct Minimal Session Language

If we consider only one minimal authentication attempt before reaching the accepting state or reset, the correct scenario is the word

$$w_{auth} = bp. \quad (30)$$

Under this limited scenario, the successful minimal authentication language is

$$L_{auth} = \{bp\}. \quad (31)$$

This representation is useful because the success criterion is defined not by a set of procedural conditions, but by a formal condition that the input sequence belongs to an acceptable language. In a more complex system, the language can be expanded to include additional factors, retries, timeouts, and individual blocking states, while the formalization method remains the same.

Theorem 2. For any probability distribution satisfying (9), the normalized coefficient (12) is bounded:

$$0 \leq D_{EC} \leq 1, \quad (32)$$

and $D_{EC} = 1$ then and only then when

$$p_1 = p_2 = \dots = p_n = \frac{1}{n}. \quad (33)$$

Proof. For $0 \leq p_i \leq 1$, $\log_2 p_i \leq 0$ therefore each term $-p_i \log_2 p_i$ is non-negative and $H(Q) \geq 0$.

To find the maximum, we consider the Lagrange function under the condition of normalization of probabilities:

$$\mathcal{L} = -\sum_{i=1}^n p_i \ln p_i + \lambda \left(\sum_{i=1}^n p_i - 1 \right). \quad (34)$$

The stationarity condition gives

$$\frac{\partial \mathcal{L}}{\partial p_i} = -(\ln p_i + 1) + \lambda = 0, \quad (35)$$

from which all p_i are equal. Taking into account $\sum p_i = 1$ we obtain $p_i = 1/n$. Substituting into (10) gives

$$H_{max} = -n \cdot \frac{1}{n} \log_2 \frac{1}{n} = \log_2 n. \quad (36)$$

Consequently, relation (12) belongs to the interval $[0,1]$, and unity is achieved only with uniform distribution. The theorem is proven.

Theorem 3. If D_{EC} , $BSSS$ and C belong to the interval $[0,1]$, and the weights satisfy (19), then

$$0 \leq IMSI \leq 1. \quad (37)$$

Proof. The non-negativity of all components and weights gives

$$w_1 D_{EC} \geq 0, \quad w_2 BSSS \geq 0, \quad w_3 C \geq 0, \quad (38)$$

therefore, $IMSI \geq 0$. On the other hand,

$$w_1 D_{EC} \leq w_1, \quad w_2 BSSS \leq w_2, \quad w_3 C \leq w_3. \quad (39)$$

Summing up (39) and using (19), we obtain

$$IMSI \leq w_1 + w_2 + w_3 = 1. \quad (40)$$

Thus, $IMSI$ is a convex combination of three normalized indices and always belongs to the interval $[0,1]$. The theorem is proven.

The minimum value corresponds to a simultaneously concentrated or degenerate automaton trajectory, an unstable channel, and the absence of successful sessions. The maximum is achieved only when all three components are equal to one. When interpreting the $IMSI$, it is important to keep in mind that a high integral score does not prove the cryptographic security of the system: it characterizes the stability of the observed operating mode within the selected model.

From a mathematical point of view, the proposed design guarantees four properties of the protocol logic.

First, the transitions are unambiguous: for each state and each input event, there is exactly one next step. This eliminates ambiguous processing of identical events.

Second, the order of factors is controlled: achievement q_2 is possible only after state q_1 , and state q_1 occurs only after a valid biometric event from q_0 . Consequently, a PIN cannot replace biometrics in a minimal session.

Third, there are no indeterminate states: the complete transition function returns the system to q_0 any forbidden combination. This provides a formally complete model of input processing.

Fourth, the separation of protocol and cryptographic logic: the accepting state serves as an admission condition, but the strength of the key, nonce, and AEAD algorithm is ensured by cryptographic standards, not by the properties of the automaton.

However, DFA does not automatically address all security issues. It does not determine the quality of the biometric sensor, the strength of the PIN against brute-force attacks, the policy for limiting the number of attempts, the protection of the master key, the validity of the time, the resistance of the wireless channel to an active adversary, or the correctness of the cryptographic library implementation. These components must be analyzed separately. Current

recommendations for authenticator management and authentication assurance levels are contained, in particular, in NIST. SP 800-63 B-4.

Thus, the mathematical role of DFA is to provably manage states and the sequence of steps. This is particularly useful for embedded systems, where logic is often implemented as a small set of event handlers and can be completely described by a finite number of states.

4. Discussion

The analysis shows that a finite-state machine is a convenient formal basis for multifactor authentication with a fixed factor order. Unlike describing an algorithm solely in terms of programmatic conditions, a DFA allows for the direct formulation and proof of protocol properties. For the basic three-state model, determinism, finite reachability of the accepting state, and the absence of deadlocks are proven. Safe return to q_0 makes the transition function complete and formalizes behavior in the event of error events.

The entropy characteristic complements logical analysis with observable statistics. The coefficient D_{EC} allows one to identify a strong concentration of visits in one or a few states. However, high entropy should not be interpreted as "randomness" of the DFA itself : the automaton remains deterministic, and variability arises from the distribution of external events and sessions. For the same reason, trajectory entropy cannot replace cryptographic strength analysis.

The integral metric (18) is convenient as a normalized indicator of the system's operational state. Mathematically, its boundedness is ensured only with strict normalization of all components. Therefore, the RSSI stability indicator in this article is refined to ensure that it lies within the interval $[0,1]$. This eliminates the contradiction between the channel indicator formula and the theorem on the boundedness of the integral metric.

A distinct advantage of the model is its ability to be extended without changing the underlying hardware. Adding a one-time code, a hardware token, or confirmation from a second device corresponds to the introduction of new states and input symbols. After such an extension, the reachability of receiving states, the absence of deadlocks, the permissible cycles, and the completeness of the transition function are re-checked. Consequently, DFA provides a scalable formal framework for designing more complex authentication protocols.

This article does not provide experimental values for biometric recognition FAR / FRR , Bluetooth latency , microcontroller power consumption, or attack results. These parameters should be studied using a specific hardware and software implementation. The presented mathematical model is primarily intended to verify the correctness of the control logic and construct measurable indicators of system state.

5. Conclusion

A mathematical model for multifactor authentication based on a deterministic finite automaton has been developed and systematized. The basic scheme includes three states and three types of events: successful biometric verification, successful PIN confirmation , and session reset. A complete transition function defines a secure return to the initial state for all prohibited combinations.

It is proven that the proposed DFA is deterministic, the accepting state is reachable in a finite number of steps, the reverse order of the factors does not lead to successful completion of the minimal session, and deadlocks are absent. For quantitative trajectory analysis, the normalized Shannon entropy is introduced D_{EC} and proven to be bounded by the interval $[0,1]$. The session success rate and the normalized stability indicator of the wireless channel are formalized. The integral stability metric is represented as a convex combination of the normalized components, ensuring that it belongs to the interval $[0,1]$.

It is shown that a finite-state machine should be used as a mechanism for protocol state management and cryptographic session admission. Session key generation and protection should be performed using standard cryptographic tools. This architecture separates formal authentication logic from cryptographic protection, facilitates verification of the software implementation, and is suitable for mobile and embedded devices with limited computing resources.

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Medical Sciences

PEMPHIGOID GESTATIONIS: A RARE AUTOIMMUNE BLISTERING DISORDER DURING PREGNANCY—A COMPREHENSIVE REVIEW OF IMMUNOPATHOGENESIS, PHARMACOTHERAPY STRATEGIES, PRECISION THERAPEUTICS AND EVIDENCE-BASED CLINICAL MANAGEMENT

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ABSTRACT

Pemphigoid gestationis (PG) is a rare, pregnancy-associated autoimmune subepidermal blistering disorder characterized by severe pruritus, erythematous urticarial plaques, and tense vesiculobullous lesions that predominantly develop during the second or third trimester of pregnancy. Although its estimated incidence ranges from approximately one case per 50,000–60,000 pregnancies, PG represents a clinically significant dermatological condition because of its potential maternal morbidity, recurrent nature in subsequent pregnancies, and association with adverse fetal outcomes, including preterm delivery, fetal growth restriction, and transient neonatal blistering resulting from transplacental transfer of pathogenic autoantibodies. The disorder shares immunopathological mechanisms with bullous pemphigoid but exhibits unique pregnancy-related immunological triggers involving aberrant placental expression of basement membrane antigens, maternal loss of immune tolerance, and complement-mediated inflammatory responses. Early recognition remains challenging because the initial manifestations frequently mimic other pregnancy-specific dermatoses, including polymorphic eruption of pregnancy, atopic eruption of pregnancy, intrahepatic cholestasis of pregnancy, and pustular psoriasis of pregnancy, emphasizing the importance of accurate differential diagnosis and multidisciplinary clinical management. This comprehensive review critically evaluates current knowledge regarding the epidemiology, molecular immunopathogenesis, clinical manifestations, diagnostic methodologies, pharmacotherapeutic interventions, precision therapeutic approaches, and evidence-based clinical management of pemphigoid gestationis. Particular emphasis is placed

on the immunological mechanisms responsible for disease initiation and progression, including maternal IgG1 autoantibody production against hemidesmosomal proteins, especially collagen XVII (BP180), activation of the classical complement cascade, recruitment of eosinophils, cytokine dysregulation, and subsequent dermoepidermal separation leading to blister formation. Recent advances in immunology have further demonstrated the roles of human leukocyte antigen susceptibility, placental immune dysregulation, T-helper cell imbalance, regulatory T-cell dysfunction, B-cell activation, and inflammatory chemokine signaling pathways that collectively contribute to disease expression and recurrence. Diagnostic evaluation requires integration of characteristic clinical findings with laboratory and histopathological investigations. Histopathological examination typically demonstrates subepidermal blister formation accompanied by eosinophilic infiltration, whereas direct immunofluorescence remains the diagnostic gold standard by demonstrating continuous linear complement C3 deposition, frequently accompanied by IgG, along the basement membrane zone. Additional diagnostic modalities, including indirect immunofluorescence, enzyme-linked immunosorbent assays for BP180 NC16A autoantibodies, and emerging molecular biomarkers, improve diagnostic accuracy, facilitate disease monitoring, and may contribute to individualized therapeutic decision-making. Contemporary differential diagnostic strategies are discussed to distinguish PG from other inflammatory and autoimmune dermatoses encountered during pregnancy. Current pharmacotherapeutic management aims to achieve rapid symptom control while minimizing fetal and maternal risks. First-line therapy generally consists of topical corticosteroids combined with pregnancy-compatible oral antihistamines for mild disease, whereas systemic corticosteroids, particularly prednisone or prednisolone, remain the cornerstone of treatment for moderate-to-severe disease because of their limited placental transfer and favorable safety profile when administered appropriately. Adjunctive therapies, including topical calcineurin inhibitors, corticosteroid-sparing immunosuppressive agents, intravenous immunoglobulin, plasmapheresis, immunoadsorption, and biologic therapies such as rituximab, omalizumab, and dupilumab, are critically evaluated for refractory or severe disease based on emerging clinical evidence. The review further discusses therapeutic monitoring, individualized dose optimization, postpartum management, breastfeeding considerations, recurrence prevention, and adverse-effect surveillance. Advances in precision medicine have created opportunities for personalized management of pemphigoid gestationis through biomarker-guided risk stratification, immunophenotyping, pharmacogenomic applications, targeted biologic therapy, and individualized monitoring protocols. Integration of artificial intelligence-assisted diagnostic algorithms, digital dermatology, machine-learning prediction models, and translational immunology may substantially improve diagnostic precision, optimize therapeutic selection, reduce corticosteroid exposure, and enhance maternal–fetal outcomes. Furthermore, multidisciplinary collaboration among dermatologists, obstetricians, maternal–fetal medicine specialists, immunologists, neonatologists, and clinical pharmacists is increasingly recognized as essential for comprehensive patient-centered care. The pemphigoid gestationis remains a rare yet clinically important autoimmune blistering disorder requiring prompt diagnosis, evidence-based pharmacotherapy, individualized therapeutic strategies, and continuous maternal–fetal monitoring. Ongoing advances in immunopathogenesis, molecular diagnostics, targeted immunotherapy, and precision medicine are transforming the clinical management paradigm and hold considerable promise for improving long-term maternal health, neonatal outcomes, and overall quality of life while minimizing disease recurrence and treatment-related complications. Continued translational research, international collaborative studies, and high-quality clinical trials are necessary to establish standardized treatment algorithms and optimize future therapeutic strategies for this uncommon but potentially serious pregnancy-associated autoimmune disease.

Keywords: Pemphigoid gestationis; Autoimmune blistering disease; Immunopathogenesis; Precision therapeutics; Evidence-based clinical management.

INTRODUCTION

Pemphigoid gestationis (PG), historically referred to as herpes gestationis despite having no etiological relationship with herpesvirus infection, is an uncommon but clinically significant autoimmune subepidermal blistering disorder that occurs exclusively during pregnancy or the immediate postpartum period. The disease belongs to the spectrum of autoimmune bullous diseases characterized by circulating autoantibodies directed against structural proteins of the dermoepidermal junction, resulting in complement activation, inflammatory cell recruitment, and subsequent separation of the epidermis from the underlying dermis. Although rare, with an estimated incidence of approximately one case per 50,000–60,000 pregnancies, PG represents one of the most important pregnancy-associated dermatoses because of its potential effects on maternal health, fetal well-being, pregnancy outcomes, and long-term autoimmune susceptibility. The uploaded source similarly describes PG as an infrequent autoimmune disorder characterized by intense pruritus, erythematous plaques, tense bullae, and autoantibodies directed against BP180 and BP230 proteins, with diagnosis supported by histopathology and direct immunofluorescence.

Pregnancy is accompanied by profound endocrine, immunological, vascular, metabolic, and dermatological adaptations that are essential for maintaining fetal tolerance while preserving maternal immune competence. These physiological changes alter both innate and adaptive immune responses, creating a unique immunological environment capable of protecting the semi-allogeneic fetus without completely suppressing maternal defense mechanisms. Although these adaptations are generally beneficial, they may also predispose genetically susceptible women to immune dysregulation, facilitating the development or exacerbation of autoimmune disorders. Pregnancy-specific dermatoses therefore represent a unique group of diseases in which physiological immune modulation intersects with pathological inflammatory mechanisms. Among these disorders, pemphigoid gestationis remains particularly important because its immunopathogenesis closely resembles bullous pemphigoid while simultaneously exhibiting distinctive placental immunobiology that makes the disease unique to pregnancy.

Autoimmune blistering diseases comprise a heterogeneous group of disorders characterized by the production of pathogenic autoantibodies directed against adhesion molecules responsible for maintaining epidermal integrity. These diseases are broadly classified into intraepidermal blistering disorders, including pemphigus vulgaris and pemphigus foliaceus, and subepidermal blistering disorders, including bullous pemphigoid, mucous membrane pemphigoid, epidermolysis bullosa acquisita, linear IgA bullous dermatosis, and pemphigoid gestationis. Despite differences in antigen specificity and clinical presentation, these disorders share common immunological mechanisms involving autoreactive B lymphocytes, pathogenic immunoglobulin G autoantibodies, complement activation, inflammatory cytokine release, and progressive destruction of epithelial adhesion complexes. Understanding these shared mechanisms has substantially improved the development of targeted therapeutic strategies and has provided valuable insights into the pathogenesis of autoimmune diseases beyond dermatology.

Historically, pemphigoid gestationis was first described during the nineteenth century when clinicians observed recurrent pruritic blistering eruptions occurring exclusively during pregnancy. The historical designation "herpes gestationis" originated from the grouped appearance of vesicular lesions rather than any viral association. Subsequent advances in immunopathology and molecular dermatology demonstrated that the disorder is immunologically related to bullous pemphigoid through autoantibody-mediated targeting of collagen XVII (BP180), leading to the adoption of the current terminology, pemphigoid gestationis. This change reflects a more accurate

understanding of disease biology and has facilitated standardized diagnostic criteria and international research collaboration.

Despite its rarity, PG has attracted increasing scientific attention because of advances in molecular immunology, translational medicine, and maternal–fetal immunopathology. Modern research has demonstrated that disease initiation likely originates within placental tissues, where abnormal expression of major histocompatibility complex class II molecules allows presentation of normally concealed basement membrane antigens to maternal immune cells. This process initiates autoreactive T-cell activation, stimulates B-cell differentiation into antibody-producing plasma cells, and results in the production of pathogenic IgG1 autoantibodies directed primarily against the NC16A domain of collagen XVII. These antibodies subsequently cross-react with cutaneous basement membrane antigens, activate the classical complement cascade, recruit eosinophils, neutrophils, mast cells, and macrophages, and ultimately induce dermoepidermal separation through proteolytic degradation of anchoring structures.

One of the most distinctive characteristics of pemphigoid gestationis is its close association with pregnancy-related immunological events. Unlike most autoimmune blistering diseases, PG develops almost exclusively during gestation, frequently during the second or third trimester, although first-trimester onset and postpartum presentations have also been documented. The uploaded review likewise notes that the disorder most commonly develops during the second or third trimester but may occur earlier or during the postpartum period and frequently recurs in subsequent pregnancies. The disease often improves during late pregnancy only to flare again immediately after delivery, reflecting abrupt hormonal and immunological changes accompanying parturition. Such clinical behavior strongly supports the hypothesis that placental immune regulation plays a central role in disease pathogenesis.

Recurrence represents another defining characteristic of pemphigoid gestationis. Women affected during one pregnancy have a high likelihood of recurrence during subsequent pregnancies, often with earlier onset and increased disease severity. Disease exacerbations have additionally been reported following menstruation, administration of estrogen-containing oral contraceptives, trophoblastic disease, and, rarely, gestational trophoblastic neoplasia, suggesting that hormonal fluctuations and trophoblastic tissue continue to influence autoimmune activity beyond pregnancy itself. Recognition of these recurrence patterns is essential for preconception counseling, individualized obstetric surveillance, and postpartum follow-up.

Although maternal prognosis is generally favorable with appropriate treatment, the disease may significantly impair quality of life. Severe pruritus frequently precedes blister formation and may become debilitating, interfering with sleep, psychological well-being, occupational functioning, and overall maternal health. Persistent itching often produces anxiety, depression, fatigue, and reduced health-related quality of life comparable to that observed in other chronic inflammatory dermatological disorders. Extensive blistering increases susceptibility to secondary bacterial infection, fluid loss, discomfort, and prolonged recovery, particularly when diagnosis is delayed or disease activity remains uncontrolled.

From an obstetric perspective, pemphigoid gestationis extends beyond a localized dermatological condition. Multiple observational studies have demonstrated associations between active disease and adverse pregnancy outcomes, including preterm birth, fetal growth restriction, placental insufficiency, and low birth weight. Although fetal mortality remains uncommon, careful maternal-fetal surveillance is recommended because disease severity does not always correlate directly with pregnancy complications. Passive transplacental transfer of maternal IgG autoantibodies may also produce transient neonatal pemphigoid characterized by self-limited vesiculobullous lesions in approximately 5–10% of newborns. Fortunately, neonatal disease typically resolves spontaneously as maternal antibodies disappear from the infant's circulation.

Accurate diagnosis of pemphigoid gestationis remains challenging because its early manifestations frequently resemble other pregnancy-specific dermatoses. The uploaded review emphasizes that polymorphic eruption of pregnancy, atopic eruption of pregnancy, intrahepatic cholestasis of pregnancy, and pustular psoriasis represent major differential diagnoses requiring careful clinical distinction. Clinical overlap during the initial urticarial phase often delays definitive diagnosis until vesicles and tense bullae become apparent. Consequently, histopathological examination and direct immunofluorescence have become indispensable diagnostic tools, with linear C3 deposition along the basement membrane remaining the immunopathological hallmark of the disease. Advances in serological testing, particularly enzyme-linked immunosorbent assays targeting BP180 autoantibodies, have further enhanced diagnostic precision and disease monitoring.

The growing understanding of molecular immunopathogenesis has transformed the therapeutic landscape of pemphigoid gestationis. While systemic corticosteroids remain the cornerstone of treatment for moderate-to-severe disease, increasing emphasis is being placed on steroid-sparing therapies, biologic agents, precision immunomodulation, and individualized risk stratification. Modern therapeutic approaches seek not only to suppress disease activity but also to minimize maternal adverse effects, optimize fetal safety, reduce postpartum recurrence, and improve long-term maternal outcomes. These developments underscore the need for updated evidence-based recommendations integrating advances in immunology, pharmacology, obstetrics, and precision medicine.

The immunological environment of pregnancy represents one of the most remarkable examples of physiological immune adaptation in human biology. Successful pregnancy requires the maternal immune system to tolerate the semi-allogeneic fetus while simultaneously preserving adequate defense against infectious pathogens. Rather than existing in a state of generalized immunosuppression, pregnancy is now recognized as a dynamic immunological process involving tightly regulated interactions among innate immune cells, adaptive lymphocytes, placental trophoblasts, cytokines, chemokines, hormones, and complement proteins. These coordinated mechanisms maintain maternal–fetal tolerance throughout gestation but may inadvertently predispose susceptible women to autoimmune disorders, including pemphigoid gestationis. The uploaded review similarly identifies pregnancy-specific immune alterations as central to disease development and notes that placental immune responses trigger maternal autoantibody production against BP180 and BP230 proteins.

The placenta is increasingly recognized as the initiating site of autoimmune activation in pemphigoid gestationis. Beyond its role in nutrient exchange and fetal development, the placenta functions as a highly specialized immunological organ that actively regulates maternal immune tolerance. Trophoblast cells express numerous immunomodulatory molecules that suppress excessive maternal immune activation while permitting immune surveillance against pathogens. Under physiological conditions, basement membrane proteins, including collagen XVII (BP180), remain immunologically concealed from maternal immune recognition. However, aberrant expression of major histocompatibility complex class II molecules within placental tissues may expose these normally hidden antigens to maternal antigen-presenting cells. Presentation of BP180-derived peptides activates autoreactive CD4⁺ T lymphocytes, initiating a cascade of immune events culminating in pathogenic autoantibody production.

Activation of adaptive immunity represents the central immunopathological event underlying disease development. Antigen-specific helper T lymphocytes stimulate autoreactive B cells through cytokine-mediated signaling and direct cellular interactions, promoting their differentiation into plasma cells capable of producing high-affinity immunoglobulin G1 autoantibodies directed primarily against the extracellular NC16A domain of collagen XVII. These circulating antibodies subsequently bind to homologous antigens located within the dermoepidermal junction, initiating complement activation and inflammatory tissue injury.

Although BP180 constitutes the principal pathogenic antigen, autoantibodies directed against BP230 have also been detected in a proportion of patients and may contribute to disease progression or epitope spreading during chronic inflammation. The uploaded review likewise identifies BP180 and BP230 as the principal antigenic targets responsible for autoimmune blister formation.

Collagen XVII is a transmembrane hemidesmosomal glycoprotein that plays an essential role in maintaining structural integrity between basal keratinocytes and the underlying basement membrane. Together with integrins, laminins, plectin, and additional anchoring proteins, collagen XVII stabilizes epidermal adhesion and resists mechanical stress. Binding of pathogenic autoantibodies disrupts this structural complex by initiating inflammatory signaling pathways rather than directly destroying the protein itself. Complement activation recruits inflammatory leukocytes whose proteolytic enzymes degrade extracellular matrix proteins, ultimately producing separation of the epidermis from the dermis and formation of characteristic tense subepidermal bullae.

Among the numerous immunological pathways implicated in pemphigoid gestationis, activation of the classical complement cascade occupies a particularly important position. Antibody binding to basement membrane antigens activates complement component C1, initiating sequential activation of downstream complement proteins and culminating in deposition of complement component C3 along the dermoepidermal junction. Linear C3 deposition remains the immunopathological hallmark of pemphigoid gestationis and forms the basis of diagnostic confirmation by direct immunofluorescence. The uploaded review similarly emphasizes that direct immunofluorescence demonstrating continuous linear C3 deposition along the basement membrane constitutes the diagnostic gold standard.

Complement activation generates multiple inflammatory mediators, including C3a and C5a, which function as potent chemoattractants for eosinophils, neutrophils, macrophages, and mast cells. Recruitment of these inflammatory cells amplifies tissue injury through release of proteases, reactive oxygen species, eosinophil granule proteins, matrix metalloproteinases, and pro-inflammatory cytokines. Progressive degradation of anchoring filaments weakens dermoepidermal adhesion until mechanical stress ultimately produces blister formation. Histopathological examination therefore characteristically demonstrates eosinophil-rich inflammatory infiltrates accompanied by subepidermal cleft formation, findings that closely correspond to the pathological description presented in the uploaded review.

Eosinophils occupy a particularly prominent role within the inflammatory microenvironment of pemphigoid gestationis. Beyond serving as markers of allergic inflammation, eosinophils actively contribute to tissue destruction through secretion of eosinophil cationic protein, eosinophil peroxidase, major basic protein, and eosinophil-derived neurotoxin. These cytotoxic mediators directly injure epithelial structures while simultaneously stimulating additional inflammatory cell recruitment. Furthermore, eosinophils produce numerous cytokines and growth factors that perpetuate chronic inflammation and delay tissue repair. Increasing evidence suggests that eosinophil activation may correlate with disease activity, thereby representing a potential biomarker for therapeutic monitoring.

Cytokine dysregulation constitutes another critical component of disease pathogenesis. Pregnancy is associated with dynamic shifts in cytokine profiles that vary across gestation. During normal pregnancy, anti-inflammatory cytokines contribute to fetal tolerance, whereas pro-inflammatory cytokines predominate during implantation and labor. In pemphigoid gestationis, disruption of this balance favors enhanced production of inflammatory mediators, including interleukin-4, interleukin-5, interleukin-13, interleukin-17, tumor necrosis factor- α , and numerous chemokines that collectively amplify leukocyte recruitment and antibody-mediated tissue injury.

Simultaneously, regulatory cytokines responsible for maintaining peripheral immune tolerance appear insufficient to suppress autoreactive lymphocyte activation.

Regulatory T lymphocytes are fundamental mediators of maternal immune tolerance during pregnancy. These specialized lymphocytes suppress autoreactive immune responses, inhibit excessive inflammation, and promote fetal survival by limiting maternal recognition of paternal antigens. Several immunological investigations suggest that quantitative or functional abnormalities of regulatory T cells may contribute to the breakdown of immune tolerance observed in autoimmune pregnancy disorders. Reduced regulatory T-cell activity may permit expansion of autoreactive helper T cells, facilitate B-cell activation, and promote sustained autoantibody production against basement membrane proteins. Although definitive mechanisms remain under investigation, regulatory T-cell dysfunction represents an important area of ongoing translational research.

B lymphocytes likewise play indispensable roles extending beyond antibody production alone. Modern immunology recognizes B cells as multifunctional antigen-presenting cells capable of cytokine secretion, immune regulation, and interaction with helper T lymphocytes. Dysregulated B-cell maturation, defective peripheral tolerance, and prolonged plasma-cell survival may all contribute to persistent autoantibody production in pemphigoid gestationis. These observations provide a strong biological rationale for the therapeutic use of B-cell-targeted agents in severe or refractory disease.

Genetic susceptibility further influences disease development. Epidemiological studies have consistently demonstrated strong associations between pemphigoid gestationis and specific human leukocyte antigen class II haplotypes, particularly HLA-DR3 and HLA-DR4. These genetic associations suggest that antigen presentation efficiency influences susceptibility to autoimmune recognition of collagen XVII. Women possessing these haplotypes may present placental BP180-derived peptides more efficiently to helper T lymphocytes, thereby increasing the probability of autoimmune activation during pregnancy. Nevertheless, genetic predisposition alone appears insufficient for disease development, emphasizing the importance of environmental, hormonal, and immunological triggers.

Hormonal influences provide an additional explanation for the remarkable pregnancy specificity of pemphigoid gestationis. Dramatic fluctuations in estrogen, progesterone, human chorionic gonadotropin, and placental hormones alter immune cell differentiation, cytokine secretion, vascular permeability, and complement regulation throughout gestation. Abrupt endocrine changes occurring immediately after delivery likely explain the frequent postpartum exacerbations observed clinically. Likewise, recurrence during subsequent pregnancies and occasional flares associated with oral contraceptive use support an important role for reproductive hormones in disease expression. The uploaded review similarly notes recurrence in future pregnancies and occasional triggering by oral contraceptives.

Recent advances in molecular medicine have significantly expanded understanding of the signaling pathways involved in autoimmune blister formation. Intracellular kinase cascades, complement regulatory proteins, inflammatory lipid mediators, extracellular vesicles, and microRNAs are increasingly recognized as important modulators of immune activation. Although many of these molecular pathways remain incompletely characterized in pemphigoid gestationis, ongoing translational investigations continue to identify novel therapeutic targets that may permit selective immunomodulation while minimizing systemic corticosteroid exposure.

The expanding understanding of disease biology has simultaneously transformed concepts of disease classification. Rather than viewing pemphigoid gestationis solely as a pregnancy-associated skin disorder, it is increasingly recognized as a systemic autoimmune disease with complex interactions among placental biology, maternal immunology, genetics, endocrinology, dermatology, and fetal medicine. This multidisciplinary perspective has important implications for

diagnosis, therapeutic decision-making, obstetric surveillance, postpartum monitoring, and long-term patient counseling.

The clinical presentation of pemphigoid gestationis is highly characteristic once fully established; however, its initial manifestations are frequently nonspecific, contributing to delayed recognition and diagnostic uncertainty. The disease usually begins with severe pruritus that may precede visible cutaneous lesions by several days or weeks. Intense itching represents one of the earliest and most debilitating symptoms, often significantly impairing sleep quality, psychological well-being, and daily functioning. The first visible lesions typically consist of erythematous urticarial papules and plaques that characteristically originate in the periumbilical region before progressively extending to the abdomen, trunk, buttocks, and proximal extremities. As inflammatory activity increases, vesicles and tense subepidermal bullae develop upon erythematous or urticarial skin, while mucosal involvement remains uncommon compared with other autoimmune blistering diseases. The uploaded review similarly describes severe pruritus, erythematous plaques, periumbilical onset, progression to tense bullae, and spread to the trunk and extremities as hallmark clinical findings.

Although the clinical morphology eventually becomes characteristic, distinguishing pemphigoid gestationis from other pregnancy-associated dermatoses remains challenging during the early inflammatory phase. Polymorphic eruption of pregnancy, atopic eruption of pregnancy, intrahepatic cholestasis of pregnancy, and pustular psoriasis of pregnancy frequently present with overlapping symptoms, particularly generalized pruritus and erythematous cutaneous lesions. Accurate differential diagnosis is essential because these disorders differ substantially regarding immunopathogenesis, maternal prognosis, fetal risk, therapeutic approaches, and long-term follow-up. The uploaded review emphasizes the importance of obtaining a detailed obstetric history, documenting lesion distribution, evaluating symptom chronology, and recognizing disease-specific clinical patterns to facilitate appropriate diagnosis.

Comprehensive diagnostic evaluation integrates clinical assessment with histopathological, immunological, and serological investigations. Histopathological examination of lesional skin typically demonstrates subepidermal blister formation accompanied by eosinophilic spongiosis and dense eosinophilic inflammatory infiltrates within the superficial dermis. While these findings strongly support the diagnosis, histopathology alone lacks sufficient specificity to distinguish pemphigoid gestationis from other autoimmune blistering disorders. Consequently, direct immunofluorescence remains the diagnostic gold standard because of its ability to demonstrate continuous linear deposition of complement component C3, frequently accompanied by immunoglobulin G, along the basement membrane zone. The uploaded review similarly identifies histopathology and direct immunofluorescence as the principal diagnostic modalities and recognizes linear C3 deposition as the defining immunopathological feature.

Recent advances in laboratory diagnostics have substantially improved disease detection and monitoring. Enzyme-linked immunosorbent assays targeting circulating BP180 NC16A autoantibodies permit quantitative assessment of disease-specific antibody concentrations, which frequently correlate with clinical disease activity. Indirect immunofluorescence using salt-split skin substrates further assists in confirming circulating autoantibodies, while emerging molecular diagnostic technologies, including multiplex autoantibody profiling, proteomic analysis, transcriptomic sequencing, and biomarker discovery, are expanding opportunities for earlier diagnosis and individualized therapeutic monitoring. Although these advanced molecular techniques are not yet routinely incorporated into clinical practice, they represent promising tools for future precision dermatology.

The increasing availability of immunological biomarkers has transformed concepts of disease monitoring. Traditional clinical assessment based solely on lesion count and symptom severity is gradually being supplemented by objective laboratory indicators, including BP180 antibody titers,

complement activation markers, inflammatory cytokine concentrations, eosinophil-derived proteins, and circulating chemokine profiles. Such biomarkers may facilitate earlier recognition of disease recurrence, prediction of therapeutic response, and optimization of corticosteroid tapering strategies. Integration of laboratory biomarkers with clinical scoring systems may ultimately permit individualized treatment algorithms that minimize both disease relapse and treatment-associated toxicity.

Management of pemphigoid gestationis requires careful balancing of maternal disease control with fetal safety. Because most patients are pregnant at presentation, therapeutic decision-making differs substantially from that of other autoimmune blistering disorders encountered outside pregnancy. The primary therapeutic objectives include rapid suppression of inflammatory activity, effective relief of severe pruritus, prevention of new blister formation, preservation of maternal quality of life, minimization of fetal exposure to potentially harmful medications, reduction of postpartum flares, and prevention of long-term complications. Successful management therefore depends upon close collaboration among dermatologists, obstetricians, maternal–fetal medicine specialists, neonatologists, immunologists, and clinical pharmacists.

Current evidence-based pharmacotherapy remains centered on corticosteroid therapy. Mild localized disease generally responds to topical corticosteroids combined with emollients and pregnancy-compatible oral antihistamines for symptomatic relief of pruritus. Moderate-to-severe disease usually requires systemic corticosteroids, particularly prednisone or prednisolone, because placental metabolism limits fetal exposure while providing effective suppression of autoimmune inflammation. Treatment is individualized according to disease severity, gestational age, maternal comorbidities, and anticipated obstetric risks. The uploaded review similarly identifies topical corticosteroids, oral antihistamines, and systemic prednisone as the principal therapeutic interventions while emphasizing the importance of minimizing corticosteroid exposure through the lowest effective dose.

Despite the effectiveness of systemic corticosteroids, prolonged treatment may produce significant maternal adverse effects, including gestational diabetes mellitus, hypertension, osteoporosis, weight gain, increased susceptibility to infection, adrenal suppression, mood disturbances, impaired wound healing, and cataract formation. Consequently, considerable research has focused on identifying steroid-sparing therapeutic alternatives capable of maintaining disease remission while reducing cumulative corticosteroid exposure. Contemporary clinical practice increasingly considers adjunctive therapies, including intravenous immunoglobulin, immunoadsorption, plasmapheresis, azathioprine during the postpartum period when appropriate, and selected biologic agents for exceptionally refractory disease. Although evidence remains limited because of the rarity of pemphigoid gestationis, accumulating case reports and observational studies suggest that targeted immunomodulatory therapies may offer substantial benefits in carefully selected patients.

The emergence of biologic therapies has fundamentally altered the treatment landscape of numerous autoimmune diseases and is beginning to influence the management of autoimmune blistering disorders. Monoclonal antibodies targeting B lymphocytes, immunoglobulin E, interleukin-4 receptor signaling, complement activation, and inflammatory cytokine pathways have demonstrated encouraging therapeutic responses in refractory bullous pemphigoid and isolated cases of pemphigoid gestationis. Rituximab, omalizumab, dupilumab, and complement-directed therapies represent important examples of targeted immunotherapy currently under investigation. Although robust randomized clinical trials remain unavailable because of disease rarity, these agents illustrate the transition from nonspecific immunosuppression toward mechanism-based precision therapeutics.

Precision medicine represents one of the most rapidly evolving concepts in contemporary clinical pharmacology. Rather than applying standardized treatment protocols to all patients, precision

medicine seeks to individualize therapy according to molecular biomarkers, genetic susceptibility, immunological phenotype, pharmacogenomic characteristics, disease severity, comorbid conditions, and predicted therapeutic response. In pemphigoid gestationis, future precision therapeutic strategies may incorporate quantitative BP180 antibody levels, complement activation profiles, cytokine signatures, HLA genotyping, eosinophil biomarkers, and digital disease monitoring to guide individualized therapeutic selection and optimize maternal–fetal outcomes. Such approaches hold considerable promise for minimizing unnecessary immunosuppression while maximizing therapeutic efficacy.

Artificial intelligence, digital dermatology, and computational medicine are expected to further transform the diagnosis and management of autoimmune blistering diseases. Machine-learning algorithms capable of analyzing clinical photographs, histopathological images, immunofluorescence patterns, laboratory biomarkers, and electronic health records may facilitate earlier diagnosis, improve differential diagnostic accuracy, predict disease recurrence, estimate therapeutic response, and support evidence-based clinical decision-making. Integration of artificial intelligence with teledermatology platforms may also improve access to specialist care, particularly in geographically underserved regions where expertise in autoimmune blistering diseases remains limited.

Beyond therapeutic innovation, patient education constitutes an indispensable component of comprehensive disease management. Women diagnosed with pemphigoid gestationis require counseling regarding disease recurrence during future pregnancies, postpartum exacerbations, potential neonatal manifestations, medication safety, breastfeeding considerations, contraception, and long-term follow-up. Psychological support should likewise be incorporated into routine care because chronic pruritus, visible skin lesions, prolonged pharmacotherapy, and concerns regarding fetal health frequently contribute to anxiety, depression, impaired body image, and diminished quality of life. Effective communication between healthcare providers and patients enhances therapeutic adherence, facilitates early recognition of disease relapse, and improves overall maternal satisfaction with care.

Despite significant progress in understanding disease biology, important knowledge gaps remain. The precise molecular mechanisms responsible for loss of maternal immune tolerance, determinants of disease recurrence, predictors of severe maternal disease, biomarkers of fetal risk, and optimal therapeutic sequencing continue to require investigation. Likewise, high-quality randomized controlled trials remain scarce because of the rarity of the disease, limiting the availability of robust evidence supporting many therapeutic recommendations. International collaborative registries, multicenter observational studies, translational immunology research, and precision medicine initiatives are therefore essential to establish standardized diagnostic criteria, evidence-based treatment guidelines, and personalized management algorithms.

The review was undertaken to synthesize current evidence regarding the epidemiology, molecular immunopathogenesis, clinical manifestations, diagnostic approaches, pharmacotherapeutic strategies, precision therapeutics, and evidence-based multidisciplinary management of pemphigoid gestationis. By integrating advances in dermatology, immunology, obstetrics, molecular medicine, clinical pharmacology, and translational therapeutics, this review aims to provide clinicians and researchers with an updated scientific framework for improving diagnostic accuracy, optimizing individualized treatment, enhancing maternal and neonatal outcomes, and identifying future directions for research into this rare but clinically significant autoimmune blistering disorder.

BACKGROUND

Pemphigoid gestationis (PG) is a rare pregnancy-specific autoimmune subepidermal blistering disorder characterized by the development of intensely pruritic urticarial plaques, papules, vesicles, and tense bullae resulting from maternal autoantibodies directed against structural components of the dermoepidermal junction. Historically referred to as *herpes gestationis*, despite lacking any association with herpesvirus infection, the condition is now recognized as a distinct autoimmune blistering disease that shares significant immunopathological features with bullous pemphigoid. The disorder most commonly manifests during the second or third trimester of pregnancy but may also occur during the first trimester or in the postpartum period. Although its reported incidence is approximately one case per 50,000–60,000 pregnancies, pemphigoid gestationis remains clinically important because of its association with considerable maternal morbidity, recurrent disease in future pregnancies, and increased risks of adverse obstetric and neonatal outcomes. The uploaded review describes PG as an uncommon autoimmune pregnancy-associated disorder characterized by intense pruritus, erythematous plaques, tense bullae, and maternal autoantibodies against BP180 and BP230 proteins, with recurrence frequently occurring in subsequent pregnancies.

The pathogenesis of pemphigoid gestationis reflects a complex interaction between pregnancy-associated immunological adaptations, genetic susceptibility, placental immune dysregulation, complement activation, and autoantibody-mediated tissue injury. Current evidence indicates that abnormal expression of major histocompatibility complex class II molecules within placental tissues exposes collagen XVII (BP180) and related basement membrane proteins to the maternal immune system, triggering autoreactive T-cell activation and B-cell differentiation into plasma cells producing pathogenic IgG1 autoantibodies. These antibodies subsequently bind to basement membrane antigens in the skin, activate the classical complement cascade, recruit eosinophils and other inflammatory cells, and ultimately induce dermoepidermal separation with formation of characteristic subepidermal blisters. The uploaded review similarly explains that maternal antibodies directed against BP180 and BP230 proteins initiate inflammation at the dermoepidermal junction, resulting in blister formation through separation of the epidermis from the dermis.

Clinically, pemphigoid gestationis often begins with severe pruritus before the appearance of visible cutaneous lesions. The eruption classically originates around the umbilical region and subsequently extends to the abdomen, trunk, buttocks, and extremities, eventually progressing to tense vesicles and bullae. Because early manifestations resemble other pregnancy-specific dermatoses, including polymorphic eruption of pregnancy, atopic eruption of pregnancy, intrahepatic cholestasis of pregnancy, and pustular psoriasis of pregnancy, diagnosis may be delayed during the initial inflammatory stage. Histopathological examination typically demonstrates subepidermal blister formation accompanied by eosinophilic infiltration, whereas direct immunofluorescence showing continuous linear complement C3 deposition along the basement membrane remains the diagnostic gold standard. Advances in serological testing, particularly enzyme-linked immunosorbent assays detecting circulating BP180 autoantibodies, have further improved diagnostic sensitivity and disease monitoring. The uploaded review likewise emphasizes careful clinical evaluation, histopathology, and direct immunofluorescence as essential components of diagnosis.

The management of pemphigoid gestationis requires an individualized multidisciplinary approach that balances effective disease control with maternal and fetal safety. Mild disease is generally managed using topical corticosteroids, emollients, and pregnancy-compatible antihistamines, whereas moderate-to-severe disease frequently necessitates systemic corticosteroid therapy, particularly prednisone or prednisolone, because of their favorable placental metabolism and established efficacy. Women with refractory disease may require additional immunomodulatory

interventions, including intravenous immunoglobulin, plasmapheresis, immunoadsorption, or selected biologic therapies under specialist supervision. Close obstetric monitoring is recommended because active disease has been associated with preterm birth, fetal growth restriction, and transient neonatal pemphigoid resulting from passive transplacental transfer of maternal autoantibodies. The uploaded review similarly highlights topical corticosteroids, oral antihistamines, systemic corticosteroids, patient education, multidisciplinary management, and careful maternal–fetal monitoring as the foundation of evidence-based treatment.

Recent advances in immunology, molecular dermatology, clinical pharmacology, and precision medicine have substantially improved understanding of the immunopathogenesis and therapeutic management of pemphigoid gestationis. Novel insights into complement regulation, cytokine signaling, eosinophilic inflammation, B-cell biology, pharmacogenomics, biomarker-guided treatment selection, and targeted biologic therapies have expanded opportunities for individualized patient care while minimizing corticosteroid-related toxicity. Emerging technologies, including artificial intelligence-assisted diagnostics, digital dermatology, molecular biomarker profiling, and translational immunology, are expected to further refine diagnostic accuracy and therapeutic decision-making. Nevertheless, significant challenges remain because the rarity of the disease limits the availability of randomized clinical trials and universally accepted treatment guidelines. Consequently, continued international collaboration, multicenter research, and high-quality translational studies remain essential for optimizing evidence-based clinical management and improving maternal and neonatal outcomes in patients affected by this uncommon but clinically important autoimmune blistering disorder.

Although pemphigoid gestationis is classified as a dermatological disease, its clinical significance extends far beyond cutaneous manifestations because it involves complex interactions between maternal immunity, placental biology, fetal development, and systemic inflammatory responses. Pregnancy represents a unique immunological condition in which maternal tolerance toward fetal antigens must be maintained while preserving effective host defense mechanisms. This delicate immunological balance is achieved through coordinated regulation of innate and adaptive immune responses, alterations in cytokine production, hormonal modulation, and placental immune surveillance. Disruption of these regulatory mechanisms may result in the breakdown of maternal immune tolerance, leading to autoimmune activation against basement membrane proteins expressed in both placental and cutaneous tissues. Consequently, pemphigoid gestationis has become an important model for understanding the relationship between pregnancy-associated immune regulation and autoimmune disease development.

From a molecular perspective, collagen XVII (BP180) serves as the principal autoantigen responsible for disease initiation. This transmembrane hemidesmosomal protein is essential for maintaining stable adhesion between basal keratinocytes and the underlying basement membrane. Under physiological conditions, collagen XVII contributes to the structural integrity of the dermoepidermal junction by interacting with laminins, integrins, BP230, plectin, and other anchoring proteins. During pemphigoid gestationis, maternal IgG1 autoantibodies directed against the extracellular NC16A domain of BP180 initiate activation of the classical complement pathway, resulting in linear deposition of complement component C3 along the basement membrane. Subsequent recruitment of eosinophils, neutrophils, mast cells, and macrophages amplifies inflammatory injury through the release of proteolytic enzymes, reactive oxygen species, and inflammatory cytokines, ultimately producing dermoepidermal separation and blister formation. Genetic susceptibility significantly contributes to disease development. Numerous immunogenetic investigations have demonstrated strong associations between pemphigoid gestationis and human leukocyte antigen (HLA) class II alleles, particularly HLA-DR3 and HLA-DR4, suggesting that antigen presentation plays a pivotal role in disease initiation. Women carrying these susceptibility alleles appear more likely to develop autoreactive immune responses against

placental BP180 during pregnancy. Nevertheless, genetic predisposition alone does not fully explain disease occurrence, indicating that hormonal fluctuations, placental immune alterations, environmental influences, and additional epigenetic factors collectively contribute to disease expression.

Clinical progression varies considerably among affected individuals. Some women experience localized urticarial eruptions with minimal blistering, whereas others develop extensive generalized bullous disease associated with severe pruritus and substantial impairment of quality of life. Disease severity may fluctuate throughout pregnancy, frequently improving during late gestation before worsening dramatically in the immediate postpartum period. Furthermore, recurrence during subsequent pregnancies is common and often presents earlier with greater clinical severity than the initial episode. These recurrent disease patterns emphasize the importance of long-term patient counseling, preconception planning, and individualized obstetric surveillance in women with a previous history of pemphigoid gestationis.

Maternal complications primarily arise from uncontrolled inflammation, persistent pruritus, extensive blistering, secondary bacterial infection, and adverse effects associated with prolonged systemic corticosteroid therapy. Although maternal mortality is exceptionally rare, chronic disease activity may significantly impair physical functioning, sleep quality, emotional well-being, and overall health-related quality of life. In addition to cutaneous manifestations, prolonged systemic inflammation may contribute to metabolic disturbances, increased healthcare utilization, and psychological distress requiring multidisciplinary support.

Fetal and neonatal outcomes have received increasing attention during the past two decades. Although most pregnancies complicated by pemphigoid gestationis result in healthy live births, epidemiological studies have reported increased frequencies of preterm delivery, fetal growth restriction, low birth weight, and placental insufficiency in women with active disease. Approximately 5–10% of neonates may develop transient blistering lesions caused by passive transplacental transfer of maternal IgG autoantibodies. Fortunately, neonatal disease is generally self-limiting and resolves spontaneously as maternal antibodies are gradually eliminated from the infant's circulation. These observations reinforce the necessity for coordinated prenatal monitoring involving dermatologists, obstetricians, maternal–fetal medicine specialists, and neonatologists.

The expanding understanding of immunopathogenesis has also transformed therapeutic strategies. Historically, treatment focused primarily on symptomatic control using topical corticosteroids and antihistamines. Contemporary management, however, increasingly incorporates immunologically targeted interventions designed to interrupt specific inflammatory pathways responsible for disease progression. Advances in biologic therapies targeting B lymphocytes, immunoglobulin E, complement activation, interleukin signaling, and eosinophilic inflammation have demonstrated promising results in refractory autoimmune blistering diseases and may provide future therapeutic alternatives for carefully selected patients with severe pemphigoid gestationis. These developments illustrate the broader transition from conventional immunosuppression toward mechanism-based precision therapeutics.

Precision medicine has become an increasingly important concept in dermatology and clinical pharmacology. Biomarker-guided treatment selection, pharmacogenomic profiling, quantitative autoantibody monitoring, and molecular characterization of immune responses provide opportunities to individualize therapeutic decision-making according to disease phenotype and predicted treatment response. Emerging technologies, including artificial intelligence-assisted image analysis, digital pathology, machine-learning algorithms, and teledermatology platforms, may further improve early diagnosis, disease monitoring, therapeutic optimization, and access to specialist care. Such innovations have the potential to reduce diagnostic delays, improve maternal outcomes, minimize unnecessary corticosteroid exposure, and enhance neonatal safety.

Despite substantial scientific progress, pemphigoid gestationis remains an understudied disease because of its low incidence and the limited availability of prospective multicenter clinical trials. Current therapeutic recommendations are derived largely from observational studies, retrospective analyses, case series, and expert consensus rather than large randomized controlled trials. Consequently, important questions remain regarding optimal corticosteroid dosing, the long-term safety of biologic therapies during pregnancy, biomarker-guided treatment algorithms, predictors of disease recurrence, and personalized therapeutic approaches. Continued international collaboration, translational immunological research, pharmacogenomic investigations, and multicenter clinical studies are therefore essential to establish standardized evidence-based guidelines and improve maternal and neonatal outcomes.

The review critically examines current evidence regarding the epidemiology, immunopathogenesis, clinical manifestations, diagnostic advances, pharmacotherapy strategies, precision therapeutics, and multidisciplinary evidence-based management of pemphigoid gestationis. By integrating recent developments in dermatology, immunology, obstetrics, molecular medicine, and clinical pharmacology, this review aims to provide healthcare professionals and researchers with an updated scientific framework for improving early diagnosis, optimizing individualized treatment, reducing disease-related morbidity, and identifying future research priorities for this rare but clinically significant autoimmune blistering disorder.

GOAL

The primary goal of this comprehensive review is to critically evaluate the current scientific evidence on pemphigoid gestationis, with particular emphasis on its epidemiology, immunopathogenesis, clinical manifestations, diagnostic approaches, pharmacotherapy strategies, precision therapeutics, and evidence-based clinical management. Furthermore, this review aims to summarize recent advances in molecular immunology, biomarker discovery, targeted immunomodulatory therapies, and multidisciplinary maternal–fetal care to enhance early diagnosis, optimize individualized treatment, minimize maternal and neonatal complications, and identify existing knowledge gaps and future research priorities for improving clinical outcomes in this rare autoimmune blistering disorder during pregnancy.

METHODOLOGY

This article was prepared as a comprehensive narrative review of the current scientific literature on pemphigoid gestationis, focusing on its epidemiology, immunopathogenesis, clinical manifestations, diagnostic approaches, pharmacotherapy strategies, precision therapeutics, and evidence-based clinical management. The review was developed through a critical synthesis of peer-reviewed publications, including original research articles, systematic reviews, meta-analyses, clinical practice guidelines, consensus statements, and authoritative textbook chapters published predominantly within the last two decades. Particular emphasis was placed on high-quality evidence addressing molecular mechanisms of disease, advances in immunology, diagnostic biomarkers, maternal–fetal outcomes, targeted immunomodulatory therapies, and multidisciplinary management. Information from the uploaded review manuscript was incorporated as a foundational source regarding the clinical presentation, pathology, diagnostic evaluation, and treatment of pemphigoid gestationis and was critically integrated with contemporary scientific evidence to provide an updated overview of the disease. The collected literature was analyzed descriptively, and findings were synthesized into thematic sections to identify current evidence, emerging therapeutic innovations, existing knowledge gaps, and future research priorities relevant to clinical practice and translational medicine.

RESULTS AND DISCUSSION

Epidemiology, Disease Burden, and Immunopathogenesis

Pemphigoid gestationis (PG) is one of the rarest autoimmune blistering diseases associated exclusively with pregnancy, yet it remains one of the most clinically significant pregnancy-specific dermatoses because of its potential impact on maternal health, fetal well-being, and future reproductive outcomes. The available evidence demonstrates that PG occurs in approximately one out of every 50,000–60,000 pregnancies worldwide, although its true incidence is likely underestimated because of frequent misdiagnosis during the early inflammatory phase and inconsistent reporting across healthcare systems. The uploaded review similarly describes PG as an uncommon autoimmune disorder affecting approximately one in 50,000–60,000 pregnancies. Although epidemiologically uncommon, the disease carries disproportionate clinical importance because it frequently presents during the second or third trimester when maternal physiological adaptations are most pronounced. Pregnancy induces extensive hormonal, metabolic, vascular, and immunological changes that collectively promote fetal tolerance while maintaining immune surveillance against infectious agents. These physiological adaptations are generally beneficial; however, they may inadvertently create conditions that favor autoimmune activation in genetically predisposed women. Consequently, PG has become an important model for understanding pregnancy-associated autoimmunity and maternal–fetal immune interactions.

One of the most notable epidemiological observations is the high recurrence rate in subsequent pregnancies. Women previously affected by PG frequently experience recurrence during later pregnancies, often with earlier onset, increased disease severity, and more extensive blistering than observed during the initial episode. This reproducible clinical pattern strongly suggests that maternal immunological memory contributes significantly to disease pathogenesis. Previous sensitization of autoreactive B lymphocytes and memory T cells likely accelerates autoantibody production during subsequent pregnancies, resulting in more rapid disease progression. The uploaded manuscript likewise emphasizes that recurrence is common and that disease severity frequently increases during future pregnancies.

Clinical observations have additionally demonstrated disease exacerbation following childbirth, spontaneous abortion, hydatidiform mole, trophoblastic disease, menstruation, and administration of estrogen-containing oral contraceptives. These associations further support the hypothesis that reproductive hormonal fluctuations and placental immune activity play central roles in disease initiation. Unlike classical autoimmune blistering diseases, PG rarely occurs outside the context of pregnancy or trophoblastic tissue, emphasizing its unique immunobiological characteristics.

The overall burden of disease extends beyond its dermatological manifestations. Severe pruritus frequently precedes blister formation and represents one of the most debilitating symptoms experienced by affected women. Persistent itching substantially interferes with sleep, physical comfort, emotional well-being, occupational functioning, and overall quality of life. Sleep deprivation, anxiety, depression, and psychological distress are frequently reported among patients with extensive disease. These psychosocial consequences are particularly important during pregnancy because maternal psychological health directly influences fetal development, maternal behavior, treatment adherence, and postpartum recovery.

Extensive blistering further contributes to disease burden through disruption of the epidermal barrier. Loss of cutaneous integrity increases susceptibility to secondary bacterial infection, localized pain, fluid loss, delayed wound healing, and pigmentation abnormalities following lesion resolution. Although permanent scarring is uncommon because blister formation remains

subepidermal, prolonged inflammatory activity may produce persistent post-inflammatory hyperpigmentation that affects cosmetic appearance and patient satisfaction.

The disease also imposes considerable healthcare utilization. Patients frequently require repeated dermatological evaluations, obstetric monitoring, laboratory investigations, histopathological examination, immunofluorescence studies, systemic pharmacotherapy, and multidisciplinary follow-up extending into the postpartum period. Hospitalization may occasionally become necessary for women with widespread blistering, uncontrolled symptoms, or significant obstetric complications. Consequently, although PG is rare, its cumulative economic and healthcare burden exceeds that expected from its incidence alone.

The immunopathogenesis of pemphigoid gestationis has become increasingly well understood over the past three decades through advances in molecular immunology, placental biology, and autoimmune dermatology. Contemporary evidence indicates that disease initiation originates within the placenta rather than the skin itself. Placental trophoblasts express multiple basement membrane proteins, including collagen XVII (BP180), that are structurally identical to those present within the cutaneous dermoepidermal junction. Under physiological circumstances, maternal immune tolerance prevents recognition of these fetal-derived antigens. However, abnormal expression of major histocompatibility complex class II molecules within placental tissues may permit presentation of BP180-derived peptides to maternal CD4-positive helper T lymphocytes, thereby initiating autoimmune sensitization.

Activation of antigen-specific helper T cells represents the central immunological event responsible for disease progression. Following antigen recognition, activated T lymphocytes release cytokines that stimulate autoreactive B-cell proliferation, differentiation, and maturation into plasma cells capable of producing high-affinity IgG1 autoantibodies directed primarily against the NC16A domain of collagen XVII. These circulating antibodies subsequently enter the systemic circulation and bind to homologous basement membrane antigens within the maternal skin. The uploaded review similarly identifies maternal autoantibodies directed against BP180 and BP230 as the principal pathogenic mechanism responsible for blister formation.

Collagen XVII functions as an essential transmembrane component of hemidesmosomes, specialized adhesion complexes responsible for maintaining structural attachment between basal keratinocytes and the basement membrane. The protein interacts with laminin-332, integrins, BP230, plectin, and additional extracellular matrix molecules to preserve mechanical stability of the epidermis. Binding of pathogenic autoantibodies does not directly destroy collagen XVII but instead activates inflammatory pathways that progressively weaken dermoepidermal adhesion through complement activation and leukocyte-mediated proteolysis.

Among all immunological mechanisms involved in PG, activation of the classical complement pathway appears particularly important. Antibody binding activates complement component C1, initiating sequential activation of downstream complement proteins culminating in deposition of complement component C3 along the basement membrane. Continuous linear C3 deposition constitutes the characteristic immunopathological hallmark observed by direct immunofluorescence and remains the most reliable diagnostic finding. The uploaded review similarly identifies linear C3 deposition as the gold-standard immunopathological feature distinguishing PG from other pregnancy-associated dermatoses.

Complement activation generates potent inflammatory mediators, particularly C3a and C5a, which recruit eosinophils, neutrophils, macrophages, mast cells, and additional leukocytes to the dermoepidermal junction. These inflammatory cells release numerous proteolytic enzymes, reactive oxygen species, cytokines, chemokines, leukotrienes, and matrix metalloproteinases that progressively degrade anchoring filaments connecting the epidermis to the dermis. Once structural integrity becomes sufficiently compromised, mechanical stress produces separation of

the epidermis from the underlying dermis, resulting in formation of characteristic tense subepidermal bullae.

Eosinophils represent one of the dominant inflammatory cell populations observed in PG lesions. Histopathological examination consistently demonstrates dense eosinophilic infiltrates surrounding subepidermal blisters, reflecting their important role in disease progression. Activated eosinophils release eosinophil cationic protein, eosinophil peroxidase, major basic protein, and numerous inflammatory mediators that directly contribute to tissue injury while simultaneously amplifying recruitment of additional leukocytes. These findings correspond closely with the histopathological features summarized in the uploaded review.

Recent molecular investigations have expanded understanding of cytokine-mediated inflammation in PG. Dysregulated production of interleukin-4, interleukin-5, interleukin-13, tumor necrosis factor-alpha, interleukin-17, eotaxin, and multiple chemokines appears to sustain chronic inflammatory activity throughout disease progression. Simultaneously, impaired regulatory T-cell function reduces peripheral immune tolerance, allowing persistence of autoreactive lymphocyte populations and continued autoantibody production. These complex cytokine networks provide important therapeutic targets for emerging biologic therapies designed to selectively inhibit specific inflammatory pathways rather than producing generalized immunosuppression.

Genetic susceptibility further contributes to disease pathogenesis. Strong associations between PG and HLA-DR3 as well as HLA-DR4 suggest that antigen presentation efficiency significantly influences autoimmune activation. Nevertheless, the relatively low disease incidence despite widespread distribution of these alleles indicates that genetic predisposition alone is insufficient. Disease expression instead appears to require interaction among susceptible genetic backgrounds, placental immune dysregulation, hormonal changes, complement activation, and environmental influences. This multifactorial pathogenesis explains the considerable heterogeneity observed in disease severity, recurrence, and therapeutic response among affected women.

The findings demonstrate that pemphigoid gestationis represents far more than a localized blistering disorder. Rather, it is a complex systemic autoimmune disease arising from interactions among placental immunology, maternal adaptive immunity, complement activation, inflammatory cell recruitment, genetic susceptibility, and endocrine regulation. Understanding these mechanisms provides the scientific foundation for contemporary diagnostic strategies and increasingly targeted pharmacotherapeutic interventions, which are discussed in the following sections.

Clinical Manifestations, Diagnostic Evaluation, Histopathology, and Emerging Biomarkers

The clinical manifestations of pemphigoid gestationis (PG) reflect the progressive autoimmune destruction of the dermoepidermal junction and vary according to disease severity, gestational age, immunological activity, and individual susceptibility. Although the disease exhibits a characteristic clinical evolution, considerable heterogeneity exists among patients, often resulting in delayed recognition during the early inflammatory phase. The available evidence demonstrates that intense pruritus is almost universally the initial symptom and frequently precedes visible skin lesions by several days or weeks. This prodromal period is clinically important because many patients initially receive alternative diagnoses before the development of the classic vesiculobullous eruption. The uploaded review likewise emphasizes that severe pruritus often represents the earliest manifestation before progression to erythematous plaques, vesicles, and tense bullae.

Pruritus associated with PG is generally severe, persistent, and often disproportionate to the extent of visible skin involvement. Unlike ordinary pregnancy-related itching, autoimmune-mediated pruritus results from inflammatory cytokines, complement activation products,

eosinophilic mediators, mast-cell degranulation, and neural sensitization occurring within inflamed skin. Histamine contributes only partially to symptom development; consequently, antihistamines alone frequently provide incomplete symptomatic relief. Persistent itching significantly affects maternal quality of life by disrupting sleep, impairing concentration, increasing fatigue, and contributing to anxiety and depressive symptoms. These observations highlight that symptom burden should not be underestimated even in patients with relatively limited blister formation.

The earliest visible lesions typically appear as erythematous urticarial papules and plaques surrounding the umbilicus. Periumbilical involvement represents one of the most useful clinical clues distinguishing PG from polymorphic eruption of pregnancy, which generally spares the umbilicus and instead develops within abdominal striae. As disease activity increases, lesions progressively extend to the abdomen, trunk, buttocks, upper thighs, and proximal extremities. Vesicles subsequently evolve into tense subepidermal bullae containing clear serous fluid. Because blister roofs remain intact owing to the subepidermal level of cleavage, ruptured lesions are less fragile than those observed in intraepidermal blistering diseases such as pemphigus vulgaris.

Disease progression varies considerably among affected women. Some patients experience localized inflammatory plaques with only occasional blister formation, whereas others develop extensive generalized bullous eruptions involving large areas of the trunk and extremities. Facial involvement is uncommon, while mucosal lesions occur infrequently compared with other autoimmune blistering disorders. Nail abnormalities and permanent scarring are rare because the basement membrane generally regenerates after inflammation subsides. Nevertheless, prolonged inflammation may leave residual post-inflammatory hyperpigmentation that gradually fades over several months following disease resolution.

An important clinical characteristic of PG is its fluctuating disease course throughout pregnancy. Many patients experience gradual worsening during the second and third trimesters, partial improvement during late gestation, and abrupt exacerbation immediately after delivery. Postpartum flares are believed to result from rapid endocrine changes together with restoration of maternal immune responsiveness following placental delivery. The uploaded review similarly notes that lesions frequently recur during the postpartum period despite temporary improvement before childbirth.

Long-term follow-up studies demonstrate that recurrence occurs in the majority of subsequent pregnancies, often with earlier onset and greater severity than the initial episode. Furthermore, isolated disease flares have been reported following menstruation, estrogen-containing oral contraceptive use, and trophoblastic disease, emphasizing the continuing influence of reproductive hormonal changes on autoimmune activity. These recurrence patterns reinforce the importance of preconception counseling and individualized obstetric planning for women with previous disease.

The differential diagnosis of PG remains challenging because several pregnancy-associated dermatoses present with similar clinical features. Polymorphic eruption of pregnancy usually develops during the late third trimester, begins within abdominal striae, and rarely progresses to blister formation. Atopic eruption of pregnancy frequently occurs earlier in gestation and is associated with a personal or family history of atopic disease. Intrahepatic cholestasis of pregnancy produces generalized pruritus without primary inflammatory skin lesions and is associated with elevated serum bile acids rather than autoimmune blister formation. Pustular psoriasis of pregnancy presents with sterile pustules accompanied by systemic symptoms including fever and electrolyte disturbances. The uploaded review appropriately emphasizes the importance of detailed clinical history, lesion distribution, obstetric history, and associated systemic findings for accurate differentiation among these pregnancy-specific dermatoses.

Accurate diagnosis requires integration of clinical findings with histopathological and immunological investigations. Skin biopsy remains an essential diagnostic procedure whenever vesicles or bullae develop during pregnancy. Histopathological examination typically demonstrates a subepidermal blister accompanied by eosinophilic spongiosis and dense eosinophilic inflammatory infiltrates within the superficial dermis. Although these findings strongly support PG, similar pathological features may occur in other autoimmune blistering disorders, necessitating additional immunological confirmation.

Direct immunofluorescence continues to represent the diagnostic gold standard. Examination of perilesional skin characteristically demonstrates continuous linear deposition of complement component C3 along the basement membrane zone, frequently accompanied by linear IgG deposition. The predominance of complement deposition reflects the fundamental role of complement activation in disease pathogenesis and distinguishes PG from many inflammatory dermatoses lacking immune complex deposition. The uploaded review likewise identifies direct immunofluorescence demonstrating linear C3 deposition as the definitive diagnostic investigation. Serological investigations have undergone substantial advancement during the past two decades. Enzyme-linked immunosorbent assays targeting the NC16A domain of BP180 provide highly sensitive and specific detection of circulating pathogenic autoantibodies. Quantitative BP180 antibody concentrations frequently parallel disease activity and therefore provide useful biomarkers for monitoring therapeutic response, predicting relapse, and guiding corticosteroid tapering. Indirect immunofluorescence performed using salt-split skin substrates further confirms circulating basement membrane autoantibodies in selected patients.

Beyond conventional serological testing, emerging biomarker research is transforming diagnostic evaluation. Circulating cytokine profiles, complement activation products, eosinophil-derived proteins, chemokine concentrations, extracellular vesicles, and microRNA expression patterns have demonstrated potential value for assessing inflammatory activity. Although these biomarkers remain primarily research tools, they may eventually facilitate earlier diagnosis, objective disease monitoring, individualized therapeutic selection, and prediction of maternal and fetal outcomes. Advances in molecular pathology have likewise improved understanding of tissue injury mechanisms. Immunohistochemical analyses reveal increased expression of inflammatory mediators, matrix metalloproteinases, adhesion molecules, and complement regulatory proteins within lesional skin. Transcriptomic investigations have identified differential expression of genes regulating immune activation, extracellular matrix remodeling, apoptosis, oxidative stress, and cytokine signaling. These molecular observations provide important insights into disease biology while simultaneously identifying potential therapeutic targets.

Digital pathology has emerged as another promising innovation. High-resolution whole-slide imaging combined with artificial intelligence permits automated recognition of histopathological features including eosinophilic infiltration, basement membrane disruption, and blister morphology. Machine-learning algorithms trained using large dermatopathology datasets may ultimately enhance diagnostic consistency while reducing observer variability, particularly in centers lacking specialist dermatopathology expertise.

Similarly, artificial intelligence-assisted dermatology is becoming increasingly relevant for autoimmune blistering diseases. Image-recognition systems capable of analyzing clinical photographs may assist clinicians in distinguishing PG from other pregnancy-associated dermatoses based on lesion morphology, anatomical distribution, color variation, and blister characteristics. Integration of clinical imaging with laboratory biomarkers, histopathological findings, and electronic health records may further improve diagnostic accuracy through comprehensive decision-support systems.

Maternal evaluation should extend beyond dermatological assessment alone. Obstetric monitoring remains essential because disease activity has been associated with increased risks of

placental dysfunction, fetal growth restriction, preterm delivery, and neonatal blistering resulting from passive transfer of maternal IgG autoantibodies. Consequently, serial fetal growth assessment, antenatal surveillance, and coordinated maternal–fetal management are recommended throughout pregnancy, particularly in women with extensive disease requiring systemic corticosteroid therapy.

The contemporary evidence demonstrates that accurate diagnosis of pemphigoid gestationis depends upon comprehensive clinical evaluation supported by histopathology, direct immunofluorescence, and disease-specific serological testing. Emerging molecular biomarkers, digital pathology, artificial intelligence, and precision diagnostic technologies are expected to further improve early disease recognition, objective monitoring, and individualized patient management. These advances establish the diagnostic foundation necessary for evidence-based pharmacotherapy and targeted immunomodulatory treatment, which are discussed in the following section.

Evidence-Based Pharmacotherapy Strategies, Precision Therapeutics, and Multidisciplinary Clinical Management

The management of pemphigoid gestationis (PG) has evolved considerably over the past several decades owing to advances in immunology, clinical pharmacology, maternal–fetal medicine, and precision therapeutics. Contemporary treatment strategies extend beyond simple symptomatic control and instead aim to suppress autoimmune inflammation, prevent new blister formation, alleviate severe pruritus, preserve maternal quality of life, minimize fetal exposure to potentially harmful medications, reduce postpartum recurrence, and prevent long-term complications. Because the disease occurs almost exclusively during pregnancy, therapeutic decision-making must carefully balance maternal clinical benefit against fetal safety, making PG one of the most challenging autoimmune dermatological disorders to manage.

The uploaded review identifies topical corticosteroids, oral antihistamines, and systemic corticosteroids as the principal pharmacological interventions while emphasizing multidisciplinary care, patient education, and close maternal–fetal monitoring throughout pregnancy and the postpartum period. These therapeutic principles remain consistent with contemporary international clinical practice, although increasing scientific evidence has expanded treatment options through the introduction of targeted immunomodulatory therapies and individualized precision medicine approaches.

Treatment selection depends primarily upon disease severity, gestational age, anatomical distribution of lesions, maternal comorbidities, obstetric complications, and previous therapeutic response. Women presenting with localized inflammatory plaques and limited blister formation generally respond well to conservative management consisting of topical corticosteroids, skin hydration, avoidance of mechanical irritation, and pregnancy-compatible oral antihistamines. Conversely, generalized disease characterized by extensive blistering, severe pruritus, or rapid disease progression usually requires systemic immunosuppressive therapy.

Topical corticosteroids remain the first-line pharmacological intervention for mild disease because they effectively suppress localized inflammatory activity while minimizing systemic drug exposure. Corticosteroids inhibit phospholipase A₂ activity, reduce prostaglandin and leukotriene synthesis, suppress inflammatory cytokine production, decrease eosinophil recruitment, stabilize vascular permeability, and inhibit leukocyte migration into affected skin. Low- and medium-potency preparations are generally preferred during pregnancy because they provide satisfactory anti-inflammatory efficacy with an excellent maternal and fetal safety profile when administered appropriately. High-potency corticosteroids may occasionally become necessary for localized resistant lesions but should be prescribed cautiously because prolonged extensive application has been associated with increased systemic absorption and possible fetal growth effects. Appropriate

patient education regarding application technique, treatment duration, and gradual dose reduction improves both therapeutic efficacy and medication safety.

Supportive dermatological care represents an essential component of comprehensive treatment. Regular application of fragrance-free emollients restores epidermal barrier integrity, reduces transepidermal water loss, improves skin hydration, and decreases susceptibility to secondary irritation. Gentle cleansers, loose-fitting clothing, avoidance of excessive heat, and meticulous wound care further enhance patient comfort while reducing the risk of bacterial superinfection. Although these interventions do not modify autoimmune activity directly, they substantially improve symptom control and overall quality of life.

Pruritus frequently remains the most distressing symptom throughout disease progression. Pregnancy-compatible second-generation antihistamines such as cetirizine and loratadine are commonly administered because of their favorable safety profile and reduced sedative effects. These agents primarily antagonize histamine H1 receptors, thereby reducing histamine-mediated itching and improving sleep quality. Nevertheless, autoimmune pruritus in PG results from multiple inflammatory mediators extending beyond histamine alone, including interleukins, eosinophilic proteins, complement activation products, and neuroimmune signaling pathways. Consequently, antihistamines should generally be considered adjunctive rather than definitive therapy.

Moderate-to-severe disease typically necessitates systemic corticosteroid therapy, which remains the cornerstone of evidence-based pharmacological management. Prednisone and prednisolone are generally preferred because placental 11 β -hydroxysteroid dehydrogenase type 2 converts a substantial proportion of active drug into inactive metabolites before fetal exposure occurs. This pharmacokinetic characteristic provides a relatively favorable fetal safety profile compared with fluorinated corticosteroids that cross the placenta more readily. Systemic corticosteroids rapidly suppress inflammatory cytokine production, inhibit complement-mediated tissue injury, decrease eosinophilic infiltration, reduce autoantibody-mediated inflammation, and effectively prevent formation of new blisters.

Despite their therapeutic effectiveness, systemic corticosteroids require careful clinical monitoring because prolonged administration may produce significant maternal adverse effects. Gestational diabetes mellitus, hypertension, excessive maternal weight gain, osteoporosis, adrenal suppression, impaired wound healing, increased susceptibility to infection, cataracts, mood disturbances, and proximal myopathy represent important corticosteroid-associated complications. Therefore, treatment should employ the lowest effective dose capable of maintaining disease control while allowing gradual tapering as clinical improvement occurs. Frequent clinical reassessment enables individualized dose adjustment according to disease activity and maternal tolerance.

The emergence of steroid-sparing therapies represents one of the most important developments in autoimmune dermatology. Although conventional immunosuppressive agents remain relatively limited during pregnancy because of fetal safety considerations, selected therapies may become appropriate during severe postpartum disease or exceptionally refractory cases managed within specialized multidisciplinary centers. Intravenous immunoglobulin has demonstrated encouraging clinical responses in patients with corticosteroid-resistant autoimmune blistering diseases. Proposed mechanisms include neutralization of pathogenic autoantibodies, inhibition of complement activation, modulation of Fc receptor signaling, suppression of inflammatory cytokines, and restoration of immune homeostasis. Because intravenous immunoglobulin does not produce generalized immunosuppression, it has become an attractive therapeutic option for carefully selected pregnant patients with severe disease.

Plasmapheresis and immunoabsorption provide additional therapeutic alternatives by directly removing circulating pathogenic autoantibodies from the maternal circulation. These

extracorporeal procedures may achieve rapid reduction of antibody concentrations and complement activation in patients with fulminant disease unresponsive to conventional pharmacotherapy. However, limited availability, procedural complexity, cost, and the need for specialized expertise currently restrict widespread clinical application.

Recent advances in molecular immunology have stimulated growing interest in biologic therapies targeting specific inflammatory pathways involved in autoimmune blistering diseases. Rituximab, a monoclonal antibody directed against the CD20 antigen expressed on B lymphocytes, depletes autoreactive B-cell populations responsible for pathogenic autoantibody production. Although experience during pregnancy remains limited, rituximab has demonstrated substantial efficacy in refractory bullous pemphigoid and isolated severe cases of pemphigoid gestationis. Similarly, omalizumab, an anti-immunoglobulin E monoclonal antibody, has shown promising therapeutic responses through modulation of mast-cell activation and eosinophilic inflammation. Dupilumab, which inhibits interleukin-4 and interleukin-13 signaling, represents another emerging biologic capable of suppressing type 2 inflammatory responses implicated in eosinophil recruitment and chronic pruritus.

Complement-directed therapeutics constitute another promising area of translational research. Because complement activation represents a fundamental pathogenic mechanism in PG, pharmacological inhibition of complement proteins may interrupt autoimmune tissue injury before blister formation occurs. Experimental complement inhibitors targeting C1, C5, and downstream inflammatory mediators are currently under investigation for various complement-mediated autoimmune diseases and may eventually expand therapeutic options for refractory PG. Precision medicine has fundamentally altered modern concepts of pharmacotherapy. Rather than applying identical treatment protocols to all patients, individualized therapeutic strategies seek to integrate molecular biomarkers, autoantibody concentrations, genetic susceptibility, immunophenotypic characteristics, disease severity, obstetric status, and predicted pharmacological response into clinical decision-making. Quantitative BP180 autoantibody titers, complement activation profiles, eosinophil biomarkers, inflammatory cytokine signatures, and HLA genotyping may eventually facilitate individualized therapeutic algorithms capable of maximizing efficacy while minimizing unnecessary immunosuppression.

Pharmacogenomics likewise offers considerable future potential. Genetic variation affecting corticosteroid metabolism, glucocorticoid receptor sensitivity, cytokine signaling, complement regulation, and immune-cell activation may partly explain the marked variability observed in therapeutic response among patients with PG. Identification of pharmacogenomic biomarkers may ultimately permit personalized drug selection, optimized dosing strategies, reduced adverse effects, and improved long-term disease control.

The integration of artificial intelligence into clinical pharmacology represents another emerging innovation. Machine-learning algorithms capable of analyzing electronic health records, laboratory biomarkers, clinical photographs, histopathological findings, and treatment outcomes may facilitate individualized prediction of disease severity, therapeutic response, recurrence risk, and medication-related adverse effects. Such decision-support systems have the potential to enhance evidence-based prescribing while reducing unnecessary exposure to systemic corticosteroids.

Successful management extends beyond pharmacological intervention alone. Optimal outcomes require coordinated multidisciplinary collaboration involving dermatologists, obstetricians, maternal–fetal medicine specialists, neonatologists, immunologists, pathologists, nurses, and clinical pharmacists. Dermatologists direct diagnosis and immunomodulatory therapy, obstetricians monitor fetal development and pregnancy progression, maternal–fetal medicine specialists evaluate obstetric complications, neonatologists assess newborns for transient autoimmune manifestations, and clinical pharmacists optimize medication safety, monitor drug

interactions, counsel patients regarding adherence, and provide pharmacovigilance throughout pregnancy and breastfeeding.

Patient education remains indispensable for long-term disease management. Women should receive comprehensive counseling regarding disease recurrence during future pregnancies, postpartum exacerbations, medication adherence, corticosteroid adverse effects, neonatal monitoring, breastfeeding considerations, contraceptive planning, and the importance of regular follow-up. Education empowers patients to recognize early signs of relapse, seek timely medical attention, and actively participate in shared therapeutic decision-making. Collectively, these evidence-based pharmacotherapeutic and multidisciplinary strategies have substantially improved maternal disease control while enhancing fetal safety, illustrating the transition from generalized immunosuppression toward individualized, mechanism-based precision therapeutics in the management of pemphigoid gestationis.

Maternal–Fetal Outcomes, Prognosis and Clinical Implications

Pemphigoid gestationis (PG) is increasingly recognized as a systemic autoimmune disease whose consequences extend beyond dermatological manifestations to influence maternal health, fetal development, neonatal adaptation, and long-term reproductive planning. Although the disease is generally associated with favorable maternal survival and spontaneous remission following pregnancy, active autoimmune inflammation may substantially affect pregnancy outcomes when diagnosis is delayed or disease activity remains poorly controlled. Consequently, current evidence emphasizes that successful management requires not only suppression of cutaneous inflammation but also continuous assessment of maternal and fetal well-being throughout gestation and the postpartum period.

One of the most important observations emerging from contemporary clinical studies is the relationship between disease severity and adverse obstetric outcomes. While many pregnancies complicated by PG progress without significant complications, active disease has been associated with increased frequencies of preterm delivery, fetal growth restriction, low birth weight, placental insufficiency, and, less commonly, premature rupture of membranes. These complications appear to arise from systemic inflammatory activation, complement-mediated placental injury, altered placental perfusion, and persistent maternal immune dysregulation rather than direct fetal autoimmune disease. The uploaded review similarly emphasizes the importance of close fetal monitoring and multidisciplinary obstetric management because maternal disease activity may influence pregnancy outcomes.

Placental pathology has become an area of increasing scientific interest because accumulating evidence suggests that immunological alterations within placental tissues initiate disease development. Histopathological studies have demonstrated inflammatory infiltrates, complement deposition, and expression of basement membrane antigens within placental structures, supporting the concept that the placenta functions as the primary site of maternal autoimmune sensitization. These findings explain why disease activity frequently fluctuates according to gestational age and why rapid postpartum changes in immune regulation often precipitate disease exacerbations immediately after delivery.

Neonatal involvement represents another important clinical consideration. Passive transplacental transfer of maternal IgG1 autoantibodies directed against BP180 may result in transient neonatal pemphigoid characterized by vesicles, bullae, or erythematous lesions appearing shortly after birth. Fortunately, neonatal disease is generally mild and self-limiting because pathogenic maternal antibodies are gradually eliminated from the infant's circulation over several weeks. Permanent dermatological sequelae are exceptionally uncommon, and most neonates recover completely without long-term complications. Nevertheless, newborns delivered to mothers with

active PG should undergo careful dermatological evaluation and appropriate neonatal follow-up to ensure prompt recognition and supportive management when required.

The postpartum period represents one of the most clinically challenging phases of disease management. Although placental delivery removes the principal immunological trigger responsible for disease initiation, abrupt hormonal changes and restoration of maternal immune responsiveness frequently provoke temporary worsening of inflammatory activity. Many women experience disease flares within days or weeks following childbirth, necessitating continued dermatological surveillance and pharmacological adjustment during the postpartum period. The uploaded review similarly notes that postpartum recurrence is common and emphasizes the importance of continued monitoring after delivery.

Breastfeeding introduces additional therapeutic considerations. Most topical corticosteroids are compatible with lactation when applied appropriately, whereas systemic corticosteroids generally remain acceptable during breastfeeding when administered at clinically appropriate doses. Careful timing of breastfeeding relative to corticosteroid administration may further minimize neonatal drug exposure. Clinical pharmacists and maternal–fetal medicine specialists therefore play important roles in counseling mothers regarding medication safety, adherence, and infant monitoring during lactation.

Recurrence remains one of the defining characteristics of PG. Women with a previous history of the disease have a substantial risk of recurrence during future pregnancies, often with earlier onset and increased severity. This observation suggests persistence of immunological memory involving autoreactive B lymphocytes and helper T cells that become rapidly reactivated following subsequent placental antigen exposure. Consequently, women with previous PG require comprehensive preconception counseling regarding recurrence risk, anticipated clinical course, medication planning, and obstetric surveillance before future pregnancies.

Long-term prognosis for maternal health is generally favorable because most patients eventually achieve complete clinical remission after pregnancy. Nevertheless, several epidemiological investigations suggest a modest increase in susceptibility to additional autoimmune disorders, particularly autoimmune thyroid disease, Graves' disease, Hashimoto thyroiditis, vitiligo, and other organ-specific autoimmune conditions. Although causal relationships remain incompletely understood, these associations support the concept that PG reflects broader immune dysregulation extending beyond pregnancy itself. Long-term follow-up should therefore include periodic clinical assessment for associated autoimmune diseases in selected high-risk individuals. From a pharmacological perspective, continued advances in targeted immunotherapy have substantially altered expectations regarding future disease management. Conventional systemic corticosteroids remain highly effective but are limited by well-recognized adverse effects associated with prolonged administration. Consequently, increasing attention has focused on therapies capable of selectively interrupting pathogenic immune pathways while preserving normal immune function. Monoclonal antibodies directed against B lymphocytes, immunoglobulin E, interleukin signaling pathways, eosinophilic inflammation, and complement activation represent particularly promising therapeutic developments. Although current evidence primarily consists of case reports and small observational studies because of disease rarity, early clinical experience suggests that targeted biologics may significantly reduce corticosteroid dependence while improving long-term disease control.

Precision medicine is expected to further transform clinical management during the coming decade. Molecular characterization of individual patients through immunophenotyping, quantitative autoantibody profiling, cytokine analysis, pharmacogenomic testing, and biomarker-guided therapeutic selection offers the potential to individualize treatment according to disease biology rather than relying solely upon clinical severity. Such personalized approaches may enable

clinicians to predict disease recurrence, identify patients likely to benefit from biologic therapies, optimize corticosteroid tapering schedules, and minimize unnecessary drug toxicity.

Artificial intelligence and digital health technologies are likely to become increasingly important components of precision dermatology. Machine-learning algorithms capable of integrating clinical photographs, histopathological findings, laboratory biomarkers, electronic health records, and pharmacological data may assist clinicians in predicting disease progression, selecting individualized therapies, identifying early relapse, and optimizing maternal–fetal monitoring strategies. Teledermatology platforms incorporating artificial intelligence may further improve access to specialist consultation, particularly in geographically underserved regions where expertise in autoimmune blistering diseases remains limited.

Despite remarkable scientific progress, several important research challenges remain unresolved. The rarity of PG has limited the feasibility of large randomized controlled clinical trials, resulting in continued reliance on case series, retrospective studies, and expert consensus for many therapeutic recommendations. Additional research is required to define optimal corticosteroid dosing strategies, evaluate long-term safety of emerging biologic therapies during pregnancy, validate molecular biomarkers capable of predicting therapeutic response, identify genetic determinants of disease susceptibility, and establish internationally accepted evidence-based management guidelines.

International collaborative registries and multicenter prospective studies will be essential for overcoming these limitations. Global data sharing may facilitate standardized diagnostic criteria, improved epidemiological surveillance, identification of prognostic biomarkers, evaluation of maternal and neonatal outcomes, and comparison of therapeutic interventions across diverse healthcare settings. Integration of translational immunology, molecular dermatology, pharmacogenomics, and clinical pharmacology will further accelerate development of innovative therapeutic strategies capable of improving patient-centered outcomes.

From a broader public health perspective, increasing awareness among dermatologists, obstetricians, family physicians, midwives, emergency physicians, and primary healthcare providers remains essential because delayed recognition continues to represent one of the principal barriers to optimal management. Educational initiatives emphasizing early diagnosis, prompt referral, multidisciplinary collaboration, and evidence-based pharmacotherapy have the potential to substantially reduce maternal morbidity while improving fetal outcomes.

The study presented that pemphigoid gestationis is a complex autoimmune blistering disorder requiring integration of dermatology, immunology, obstetrics, molecular medicine, and clinical pharmacology. Advances in understanding disease immunopathogenesis have directly influenced diagnostic methodologies and therapeutic innovations, shifting management from generalized immunosuppression toward individualized precision therapeutics. Continued progress in biomarker discovery, targeted biologic therapy, pharmacogenomics, artificial intelligence, and multidisciplinary maternal–fetal care is expected to further improve diagnostic accuracy, optimize personalized treatment strategies, reduce corticosteroid-associated toxicity, minimize maternal and neonatal complications, and enhance long-term quality of life. Future international collaborative research will remain fundamental for establishing robust evidence-based clinical guidelines and advancing the care of women affected by this rare but clinically significant autoimmune disease.

The evidence reviewed indicates that the clinical course of pemphigoid gestationis (PG) is characterized by substantial temporal variability, with periods of exacerbation and remission influenced by gestational and postpartum immunological changes. This dynamic course has important implications for treatment planning because a therapeutic regimen that is effective during active pregnancy may require modification after delivery. Rather than considering treatment as a short-term intervention directed exclusively toward resolving skin lesions, clinical

management should be viewed as a longitudinal process extending from diagnosis through pregnancy, delivery, the postpartum period, and subsequent reproductive planning.

Recurrence represents one of the most clinically relevant characteristics of PG. Women who have previously experienced the disease may develop recurrent manifestations during subsequent pregnancies, frequently at an earlier gestational stage. This pattern is consistent with the persistence of immunological memory following the initial autoimmune response. Reactivation of autoreactive lymphocyte populations following subsequent exposure to placental antigens may accelerate BP180 autoantibody production and result in earlier clinical manifestations. The uploaded review specifically identifies recurrence in subsequent pregnancies as an important characteristic of the disease.

The recurrent nature of PG has important implications for preconception counseling. Women with a previous diagnosis should be informed that recurrence is possible and that early dermatological assessment may be appropriate if pruritus or urticarial lesions develop during a subsequent pregnancy. Early recognition may permit initiation of topical therapy before progression to extensive blistering and may reduce the need for prolonged systemic corticosteroid treatment. Preconception planning should additionally include review of previous treatment response, corticosteroid-associated adverse effects, comorbidities, and anticipated monitoring requirements.

Risk stratification may become increasingly important as precision medicine develops. Patients can potentially be categorized according to disease severity, autoantibody concentrations, extent of skin involvement, gestational timing, previous recurrence patterns, and response to treatment. Individuals with limited disease may require only topical therapy and symptomatic management, whereas patients demonstrating rapid progression, extensive bullous disease, or inadequate response to conventional therapy may require early systemic intervention. This severity-based strategy avoids both undertreatment and unnecessary exposure to systemic immunosuppression. The distinction between disease activity and treatment toxicity is particularly important. A patient may exhibit clinical improvement while continuing to experience significant adverse effects from corticosteroids. Consequently, treatment success should not be defined exclusively by disappearance of blisters. A comprehensive therapeutic assessment should consider reduction in new lesion formation, improvement in pruritus, restoration of sleep and daily functioning, reduction of inflammatory activity, maternal metabolic safety, fetal development, and overall quality of life. This multidimensional assessment is particularly relevant when deciding whether systemic corticosteroids can be tapered.

The pharmacological management of severe PG also highlights the importance of balancing maternal benefit and fetal risk. Any systemic therapy administered during pregnancy must be evaluated according to pharmacokinetic properties, placental transfer, gestational timing, cumulative exposure, and available reproductive safety data. Prednisone and prednisolone remain important systemic corticosteroids because their metabolism limits fetal exposure relative to corticosteroids that cross the placenta more extensively. Nevertheless, prolonged maternal exposure should remain carefully controlled through individualized dosing and appropriate monitoring.

The limited evidence available for refractory disease presents a major therapeutic challenge. Intravenous immunoglobulin, immunoadsorption, and plasmapheresis have been utilized in selected severe cases, but the evidence does not currently establish these interventions as universal standard therapies for PG. Their potential benefit must therefore be evaluated against procedural complexity, availability, cost, patient-specific circumstances, and the quality of supporting clinical evidence. The uploaded review identifies intravenous immunoglobulin and plasmapheresis among therapeutic approaches for severe or resistant disease while emphasizing individualized management.

Another important implication is the need for systematic documentation of treatment outcomes. Because PG is rare, individual institutions encounter relatively few patients, making standardized clinical documentation particularly valuable. Recording disease onset, gestational age, lesion distribution, BP180 antibody levels, histopathological findings, treatment regimens, corticosteroid exposure, maternal complications, delivery outcomes, neonatal manifestations, and postpartum recurrence could contribute to larger international datasets. Such registries would strengthen the evidence base and facilitate comparative evaluation of therapeutic strategies.

The rarity of PG also explains why therapeutic evidence remains heterogeneous. Randomized controlled trials are difficult to conduct because recruitment is limited, disease severity varies, and ethical considerations restrict experimental exposure during pregnancy. Consequently, clinicians frequently rely upon observational evidence, case reports, retrospective cohorts, and expert recommendations. This evidence hierarchy should be explicitly considered when interpreting claims concerning emerging therapies. A favorable outcome in an individual patient can demonstrate feasibility or biological plausibility but cannot establish population-level efficacy or safety.

Future clinical trials should therefore prioritize international collaboration and standardized outcome measures. Multicenter prospective registries could provide sufficient sample sizes to evaluate prognostic factors and treatment effectiveness more reliably than isolated institutional reports. Incorporation of patient-reported outcomes, maternal metabolic parameters, fetal outcomes, neonatal outcomes, and long-term follow-up would provide a more complete assessment of therapeutic benefit and risk.

The role of clinical pharmacists is particularly relevant in such longitudinal management. Pharmacists can help establish individualized medication plans, review corticosteroid dose and duration, identify potential interactions, monitor treatment-related toxicity, counsel patients about adherence, and contribute to pregnancy and lactation pharmacovigilance. Their participation becomes especially important when multiple specialists are involved and when therapeutic regimens change between pregnancy and postpartum periods.

The evidence further supports individualized patient education as a core component of treatment. Women should understand that PG is an autoimmune disorder rather than an infectious disease, that recurrence may occur, and that treatment aims to suppress maternal inflammation while maintaining fetal safety. Clear explanation of diagnostic procedures, expected disease progression, medication benefits and risks, and postpartum monitoring can reduce uncertainty and promote adherence. Education should also emphasize that neonatal manifestations, when they occur, are generally related to passive transfer of maternal antibodies rather than independent autoimmune disease in the newborn.

An additional consideration is the relationship between PG and future autoimmune susceptibility. The immune dysregulation underlying PG may coexist with other autoimmune disorders, although the available evidence does not establish that every affected patient will develop additional autoimmune disease. Long-term clinical follow-up should therefore remain individualized, with additional investigation guided by symptoms and relevant clinical history rather than indiscriminate screening.

Taken together, these findings reinforce the concept that pemphigoid gestationis requires a continuum-of-care model. Diagnosis should be followed by severity assessment, individualized pharmacotherapy, maternal and fetal monitoring, and evaluation of treatment response, postpartum surveillance, and reproductive counseling. The uploaded review supports this integrated approach by emphasizing diagnostic confirmation, pharmacological management, maternal–fetal monitoring, patient education, and multidisciplinary care.

The future direction of PG management therefore lies in combining established corticosteroid-based therapy with validated biomarkers and targeted immunomodulation. Such an approach

could allow clinicians to identify patients at high risk for severe disease, initiate appropriate treatment earlier, reduce cumulative corticosteroid exposure, and improve maternal and neonatal outcomes. However, implementation of precision therapeutics requires rigorous validation of biomarkers and prospective evaluation of emerging treatments before they can be incorporated into routine pregnancy care.

Therapeutic Monitoring, and Translational Perspectives

The findings synthesized in this review indicate that pemphigoid gestationis (PG) should be approached as a dynamic autoimmune disorder rather than as an isolated cutaneous eruption. Disease activity may change substantially during pregnancy and particularly after delivery, requiring repeated clinical reassessment and adjustment of therapy. The uploaded review emphasizes that management should include patient education, multidisciplinary care, and close maternal–fetal monitoring, with treatment intensity determined by disease severity.

An important result of the available evidence is the central role of individualized disease assessment. Patients with limited disease can generally be managed with topical corticosteroids and symptomatic therapy, whereas extensive blistering and severe pruritus require systemic treatment. This distinction is clinically important because unnecessary systemic corticosteroid exposure should be avoided during pregnancy, while undertreatment of severe autoimmune inflammation may itself contribute to maternal morbidity and potentially adverse obstetric outcomes. Therefore, therapeutic decisions should consider lesion extent, rate of new blister formation, intensity of pruritus, functional impairment, gestational age, maternal comorbidities, and fetal status.

Therapeutic monitoring should incorporate both clinical and immunological parameters whenever appropriate. Clinical disappearance of new blisters and reduction in pruritus remain the most immediately useful indicators of treatment response. However, quantitative measurement of circulating BP180 autoantibodies may provide complementary information regarding underlying autoimmune activity. Serial assessment may be particularly useful in patients with recurrent disease or those requiring prolonged corticosteroid therapy, although biomarker concentrations should not be interpreted independently of the clinical picture. The uploaded review identifies BP180 autoantibody testing as an important diagnostic and monitoring tool.

Corticosteroid tapering represents another critical component of management. Abrupt discontinuation after clinical improvement may be followed by recurrence, whereas unnecessarily prolonged high-dose therapy exposes the mother to avoidable adverse effects. A gradual individualized reduction based on sustained clinical remission provides a more rational strategy. Particular attention should be directed toward glucose and blood-pressure monitoring, infection surveillance, weight changes, and other corticosteroid-associated complications. This approach illustrates the importance of clinical pharmacology and pharmacovigilance in the management of PG.

The evidence also supports the importance of postpartum planning before delivery occurs. Because disease exacerbation frequently develops after childbirth, discontinuation of treatment immediately following delivery may not be appropriate for patients with active disease. Instead, clinicians should establish an individualized postpartum monitoring plan, including assessment of skin lesions, pruritus, medication requirements, breastfeeding considerations, and neonatal status. The postpartum period also provides an opportunity to reassess long-term treatment requirements because disease activity generally declines after the pregnancy-related immunological stimulus has disappeared.

Neonatal assessment should be incorporated into the management pathway because maternal IgG autoantibodies can cross the placenta. Although neonatal manifestations are generally

transient, clinicians should examine newborns for vesicles, bullae, erythematous lesions, and other cutaneous abnormalities. Communication between maternal dermatology and neonatal teams facilitates rapid recognition and appropriate supportive management when neonatal disease occurs.

Another major finding concerns the importance of differentiating PG from other pregnancy-associated dermatoses. Early inflammatory PG may resemble polymorphic eruption of pregnancy or other pruritic disorders, making clinical diagnosis alone unreliable. The combination of characteristic periumbilical lesions, progression to tense bullae, histopathology, direct immunofluorescence, and BP180 serology provides a substantially stronger diagnostic framework than any individual feature. The uploaded review specifically identifies the combination of clinical assessment, biopsy, direct immunofluorescence, and serological investigation as central to accurate diagnosis.

From a translational perspective, the immunopathogenesis of PG provides several potential therapeutic targets. Autoantibody production, complement activation, eosinophil recruitment, cytokine signaling, and tissue-level inflammatory amplification represent distinct stages of the pathogenic cascade. Therapeutic intervention at these levels could theoretically interrupt disease progression while reducing dependence on broad immunosuppression. However, the evidence base for many targeted interventions remains substantially weaker than that for corticosteroids, and treatment during pregnancy requires particularly rigorous safety assessment.

This limitation is important when interpreting reports of biologic therapies in PG. Dramatic responses in individual patients can provide valuable mechanistic evidence but cannot automatically establish comparative efficacy or safety. Because PG is rare, much of the literature concerning refractory disease consists of case reports and small case series. Such evidence is useful for generating therapeutic hypotheses but should be distinguished from evidence obtained through controlled clinical trials. Consequently, biologic treatment should generally be reserved for carefully selected refractory cases under specialist multidisciplinary supervision rather than regarded as routine first-line therapy.

The same principle applies to other steroid-sparing approaches, including intravenous immunoglobulin, plasmapheresis, and immunoadsorption. These interventions may be valuable in severe treatment-resistant disease, particularly when conventional corticosteroid therapy is inadequate or associated with unacceptable toxicity. Nevertheless, their availability, cost, procedural requirements, and limited pregnancy-specific evidence restrict their universal application.

Clinical pharmacists have an important role within this therapeutic framework. Pharmacotherapeutic review should include medication reconciliation, assessment of cumulative corticosteroid exposure, identification of drug interactions, evaluation of contraindications, counseling regarding administration and adherence, and monitoring for adverse drug reactions. In pregnancy, pharmacotherapy assessment must additionally consider placental transfer, gestational age, maternal physiological changes, lactation, and neonatal exposure. This comprehensive approach transforms medication management from simple drug selection into individualized pharmacotherapy optimization.

The psychological dimension of PG should also be incorporated into outcome assessment. Severe pruritus, visible bullae, fear of fetal complications, uncertainty regarding treatment safety, and concern about recurrence may produce substantial emotional distress. Patient-centered management should therefore include clear explanation of the disease mechanism, realistic expectations regarding treatment response, discussion of recurrence risk, and appropriate psychological support. Improving communication may increase treatment adherence and reduce anxiety associated with pregnancy and autoimmune disease.

The continuing evidence indicates that optimal management of pemphigoid gestationis depends upon integration of accurate diagnosis, severity-based pharmacotherapy, longitudinal disease monitoring, maternal–fetal surveillance, pharmacovigilance, patient education, and multidisciplinary care. The uploaded review provides the clinical foundation for this integrated approach, particularly its emphasis on recognition of characteristic clinical features, immunopathological confirmation, corticosteroid-based treatment, and continued monitoring through pregnancy and the postpartum period.

The major future priority is therefore not simply the discovery of additional immunosuppressive agents but the development of validated, pregnancy-specific, biomarker-guided therapeutic algorithms. Such algorithms could combine clinical severity, BP180 autoantibody concentrations, immunological biomarkers, maternal risk factors, gestational age, and treatment response to determine the safest and most effective intervention for each patient. This represents the logical progression from conventional disease management toward precision therapeutics and provides an important direction for future research into pemphigoid gestationis.

Emerging Research, Precision Medicine, Pharmacovigilance, Clinical Challenges, and Future Directions

The rapid expansion of translational immunology has significantly improved understanding of the molecular mechanisms underlying pemphigoid gestationis (PG), providing new opportunities for individualized diagnosis and therapeutic intervention. Historically, clinical management relied primarily on suppression of generalized inflammation through corticosteroid therapy because the immunopathological basis of the disease remained poorly understood. Contemporary research, however, has demonstrated that PG is a highly organized autoimmune disorder involving complex interactions among placental immunology, adaptive immune responses, complement activation, eosinophilic inflammation, cytokine dysregulation, and genetic susceptibility. These discoveries have shifted clinical attention toward precision medicine approaches capable of targeting specific molecular pathways responsible for disease progression rather than relying exclusively on nonspecific immunosuppression.

One of the most important advances in recent years has been the identification of biomarkers capable of reflecting disease activity. Circulating BP180 NC16A autoantibody concentrations have demonstrated significant correlation with disease severity in many patients, suggesting that quantitative serological monitoring may assist clinicians in evaluating therapeutic response and predicting relapse. Unlike conventional clinical assessment, which depends largely upon visible lesion severity and subjective symptom reporting, biomarker-guided monitoring offers objective measurement of immunological activity. Future integration of serial BP180 antibody measurements into routine clinical practice may facilitate individualized corticosteroid tapering while minimizing unnecessary prolonged immunosuppression.

Beyond BP180 autoantibodies, several additional biomarkers have emerged as promising indicators of inflammatory activity. Elevated circulating eosinophil counts, eosinophil cationic protein, complement activation fragments, inflammatory chemokines, interleukin-5, interleukin-13, tumor necrosis factor-alpha, and multiple Th2-associated cytokines have been associated with disease activity in autoimmune blistering disorders. Although validation studies remain limited because of the rarity of PG, these biomarkers may eventually contribute to comprehensive disease activity indices capable of guiding individualized therapeutic decision-making.

Recent developments in genomics have further expanded understanding of disease susceptibility. Genome-wide association studies and immunogenetic investigations continue to identify polymorphisms influencing antigen presentation, complement regulation, cytokine signaling, immune-cell differentiation, and inflammatory responses. Strong associations with HLA-DR3 and HLA-DR4 remain among the most reproducible genetic findings; however, additional susceptibility

loci are increasingly being recognized through high-throughput sequencing technologies. Improved understanding of genetic predisposition may ultimately facilitate identification of women at increased risk before pregnancy, allowing enhanced surveillance and early intervention. Epigenetic regulation has also emerged as an important research area. DNA methylation, histone modification, chromatin remodeling, and non-coding RNA expression influence immune-cell differentiation without altering the underlying genetic sequence. Pregnancy itself induces profound epigenetic alterations that modify maternal immune tolerance and inflammatory responsiveness. Dysregulation of these mechanisms may contribute to breakdown of immune tolerance toward placental BP180, thereby initiating autoimmune activation. Investigation of epigenetic pathways may identify novel therapeutic targets capable of restoring physiological immune regulation while avoiding generalized immunosuppression.

MicroRNAs represent another rapidly expanding area of translational research. These short non-coding RNA molecules regulate post-transcriptional gene expression and influence multiple biological processes, including lymphocyte activation, cytokine production, complement signaling, apoptosis, and extracellular matrix remodeling. Differential expression of several microRNAs has been reported in autoimmune blistering diseases, suggesting potential utility as diagnostic biomarkers, prognostic indicators, or therapeutic targets. Future studies specifically addressing microRNA profiles in PG may provide valuable insights into disease pathogenesis and individualized treatment.

Advances in proteomics and metabolomics have similarly enhanced molecular characterization of autoimmune diseases. High-resolution mass spectrometry now permits simultaneous analysis of thousands of proteins and metabolites involved in inflammatory pathways. Such technologies may identify previously unrecognized biomarkers reflecting disease severity, treatment response, or impending relapse. Integration of proteomic and metabolomic data with genomic and immunological findings will likely contribute to increasingly sophisticated precision medicine algorithms during the coming decade.

Pharmacovigilance remains an essential component of evidence-based management because pharmacological treatment occurs during pregnancy, when both maternal and fetal safety require careful consideration. Systemic corticosteroids remain highly effective but require continuous monitoring for gestational diabetes, hypertension, excessive maternal weight gain, osteoporosis, infection, adrenal suppression, cataracts, and mood disturbances. Clinical pharmacists play a particularly important role in optimizing medication safety through dose adjustment, monitoring drug interactions, evaluating adverse reactions, counseling patients regarding medication adherence, and coordinating pharmacovigilance activities within multidisciplinary healthcare teams.

The introduction of biologic therapies has increased the importance of structured safety surveillance. Because experience with monoclonal antibodies during pregnancy remains relatively limited, comprehensive pharmacovigilance registries are required to evaluate maternal safety, fetal development, congenital anomalies, neonatal immune function, breastfeeding outcomes, and long-term child development. International pregnancy exposure registries provide valuable real-world evidence complementing conventional clinical trials, particularly for rare diseases such as PG where randomized studies remain difficult to perform.

Another important consideration involves antimicrobial stewardship. Extensive blistering occasionally predisposes patients to secondary bacterial infection requiring systemic antibiotic therapy. Appropriate microbiological evaluation, culture-directed antibiotic selection, and avoidance of unnecessary broad-spectrum antimicrobial use remain essential to reduce antimicrobial resistance while ensuring effective infection control. Clinical pharmacists and infectious disease specialists therefore contribute significantly to multidisciplinary management in complicated cases.

Patient-reported outcome measures have become increasingly important when evaluating therapeutic success. Traditional clinical endpoints, including blister counts and physician-assessed disease severity, may not fully reflect patient experience. Persistent pruritus, pain, sleep disturbance, anxiety, depression, impaired body image, and reduced quality of life often remain significant despite objective improvement in skin lesions. Incorporation of validated dermatology-specific quality-of-life instruments into routine clinical assessment permits more comprehensive evaluation of therapeutic effectiveness and supports patient-centered care.

Psychological support likewise represents an important but frequently overlooked component of comprehensive management. Pregnancy itself is associated with substantial emotional and physiological stress, and the addition of a chronic autoimmune blistering disease may further increase psychological burden. Fear regarding fetal health, medication safety, disease recurrence, and cosmetic appearance contributes to emotional distress in many affected women. Early psychological assessment, supportive counseling, and multidisciplinary communication may therefore improve treatment adherence and overall maternal well-being.

Health disparities continue to influence access to specialized care for patients with rare autoimmune diseases. Delayed diagnosis frequently results from limited awareness among primary healthcare providers, restricted availability of direct immunofluorescence laboratories, inadequate access to dermatology specialists, and regional variations in healthcare infrastructure. Educational initiatives targeting obstetricians, family physicians, emergency clinicians, dermatologists, nurses, and pharmacists are therefore essential to improve early recognition and timely referral.

From an economic perspective, PG imposes direct healthcare costs related to diagnostic investigations, pharmacotherapy, specialist consultations, hospitalization, laboratory monitoring, and long-term follow-up. Indirect costs associated with reduced productivity, prolonged maternity leave, caregiver burden, and diminished quality of life further increase the overall socioeconomic impact. Cost-effectiveness analyses comparing conventional corticosteroid therapy with emerging biologic interventions remain limited but will become increasingly important as targeted therapeutics enter routine clinical practice.

Future therapeutic development is expected to focus on highly selective immune modulation. Novel complement inhibitors, Fc receptor antagonists, neonatal Fc receptor inhibitors, cytokine-directed monoclonal antibodies, B-cell regulatory therapies, and small-molecule intracellular signaling inhibitors are currently under investigation for autoimmune blistering diseases. These targeted therapies aim to interrupt specific pathogenic mechanisms while preserving protective immune function, thereby reducing treatment-related toxicity compared with conventional systemic corticosteroids.

Artificial intelligence will likely become an integral component of future clinical practice. Machine-learning algorithms capable of integrating clinical photographs, histopathology, serological biomarkers, pharmacogenomic data, and electronic health records may facilitate earlier diagnosis, individualized therapeutic selection, prediction of disease recurrence, and optimization of maternal–fetal monitoring. Such technologies may also support multicenter research through automated data harmonization and identification of previously unrecognized disease patterns.

The available evidence demonstrates that the clinical management of pemphigoid gestationis is undergoing a profound transformation from empirical corticosteroid-based treatment toward biomarker-guided, mechanism-based, precision therapeutics. Continued advances in immunology, molecular diagnostics, pharmacogenomics, artificial intelligence, and translational medicine are expected to improve diagnostic accuracy, optimize individualized pharmacotherapy, minimize maternal and fetal complications, enhance long-term quality of life, and establish robust evidence-based international clinical guidelines. Nevertheless, because PG remains an uncommon autoimmune disorder, continued international collaboration, prospective multicenter clinical

studies, pharmacovigilance registries, and translational research will be indispensable for addressing existing knowledge gaps and further improving maternal, fetal, and neonatal outcomes.

CONCLUSION

- Pemphigoid gestationis is a rare but clinically significant pregnancy-specific autoimmune blistering disorder that presents unique diagnostic and therapeutic challenges because of its close association with maternal immune adaptation, placental immunology, and fetal well-being. Despite its low incidence, the disease has considerable clinical importance owing to its potential to cause severe maternal pruritus, extensive blistering, postpartum exacerbations, recurrent disease in subsequent pregnancies, and increased risks of adverse obstetric and neonatal outcomes. The uploaded review identifies pemphigoid gestationis as an uncommon autoimmune disorder characterized by maternal autoantibodies against BP180 and BP230, intense pruritus, blister formation, and the need for multidisciplinary clinical management.
- Current evidence demonstrates that the immunopathogenesis of pemphigoid gestationis involves a complex interaction between genetic susceptibility, placental antigen presentation, autoreactive T- and B-lymphocyte activation, complement cascade dysregulation, eosinophilic inflammation, and production of pathogenic IgG autoantibodies directed primarily against collagen XVII (BP180). These molecular mechanisms have substantially improved scientific understanding of disease biology and have facilitated the development of increasingly accurate diagnostic methods, including direct immunofluorescence, histopathology, and quantitative serological detection of BP180 autoantibodies. Emerging biomarkers and molecular diagnostic technologies are expected to further improve early diagnosis, objective disease monitoring, and individualized therapeutic decision-making.
- Pharmacotherapy remains the cornerstone of disease management. Topical corticosteroids, systemic corticosteroids, antihistamines, and supportive dermatological care continue to represent the foundation of evidence-based treatment, while intravenous immunoglobulin, plasmapheresis, immunoadsorption, and selected biologic agents provide valuable alternatives for severe or treatment-resistant cases. Advances in clinical pharmacology have shifted therapeutic strategies from generalized immunosuppression toward targeted immunomodulation, with biologic therapies directed against B cells, cytokine signaling pathways, immunoglobulin E, and complement activation representing promising future treatment options. Precision medicine, pharmacogenomics, biomarker-guided therapy, and artificial intelligence-assisted clinical decision support are expected to further optimize individualized patient care while minimizing corticosteroid-associated toxicity.
- Successful management requires close collaboration among dermatologists, obstetricians, maternal–fetal medicine specialists, neonatologists, pathologists, immunologists, and clinical pharmacists to ensure comprehensive maternal and fetal monitoring throughout pregnancy and the postpartum period. Equally important are patient education, pharmacovigilance, psychological support, preconception counseling, and long-term follow-up because recurrence during subsequent pregnancies remains common and postpartum disease flares frequently occur.
- Although remarkable progress has been achieved in understanding the molecular immunology and clinical management of pemphigoid gestationis, significant knowledge gaps remain because of the rarity of the disease and the limited availability of large prospective clinical trials. Future international collaborative research, multicenter registries, translational immunological studies, pharmacogenomic investigations, and randomized therapeutic trials are essential for establishing standardized evidence-based clinical guidelines, validating novel biomarkers, evaluating the long-term safety of emerging biologic therapies, and improving maternal, fetal, and neonatal outcomes. Continued integration of precision therapeutics with multidisciplinary evidence-based clinical

practice will ultimately enhance diagnostic accuracy, therapeutic effectiveness, and quality of life for women affected by this uncommon but important autoimmune blistering disorder during pregnancy.

RECOMMENDATIONS

- Early recognition and prompt diagnosis of pemphigoid gestationis should be prioritized to reduce maternal morbidity and improve fetal outcomes. Healthcare professionals, particularly dermatologists, obstetricians, maternal–fetal medicine specialists, and primary care physicians, should maintain a high index of suspicion in pregnant women presenting with severe pruritus, periumbilical urticarial plaques, or vesiculobullous eruptions. The uploaded review emphasizes the importance of clinical evaluation supported by histopathology, direct immunofluorescence, and appropriate therapeutic intervention.
- A multidisciplinary approach should be considered the standard of care, integrating dermatology, obstetrics, neonatology, pathology, immunology, and clinical pharmacy to optimize individualized maternal and fetal management. Treatment strategies should employ the lowest effective corticosteroid dose while incorporating supportive skin care, pregnancy-compatible antihistamines, and regular assessment for medication-related adverse effects through structured pharmacovigilance programs.
- Routine monitoring of disease activity using validated clinical assessment together with BP180 autoantibody titers, when available, is recommended to facilitate therapeutic adjustment, predict relapse, and support individualized corticosteroid tapering. Women with previous pemphigoid gestationis should receive comprehensive preconception counseling regarding recurrence risk, pregnancy planning, postpartum exacerbations, breastfeeding considerations, and long-term follow-up.
- Future research should focus on multicenter prospective clinical trials, international patient registries, and translational studies to establish standardized evidence-based management guidelines. Additional investigations evaluating pharmacogenomics, molecular biomarkers, complement inhibition, biologic therapies, and precision medicine approaches are strongly recommended to improve therapeutic efficacy while minimizing treatment-related toxicity. Furthermore, incorporation of artificial intelligence, digital dermatology, and telemedicine into clinical practice may enhance early diagnosis, facilitate specialist consultation, and improve access to high-quality care for patients with this rare autoimmune blistering disorder. Continued international collaboration is essential to advance scientific knowledge and optimize maternal, fetal, and neonatal outcomes through innovative, patient-centered, and evidence-based healthcare strategies.

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