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Table of Contents

Medical Sciences

Physical and Mathematical Sciences

Economic Sciences

Pedagogical Sciences

Philological Sciences

Agricultural Sciences

Sociological Sciences

Technical Sciences

Art History

Biological Sciences

Medical Sciences

УДК 577.1:616-074

БИОХИМИЧЕСКИЕ ИССЛЕДОВАНИЯ ОТ РУЧНЫХ МЕТОДОВ ДО АВТОМАТИЧЕСКИХ АНАЛИЗАТОРОВ И ОЦЕНКИ КАЧЕСТВА ИССЛЕДОВАНИЙ МЕЖДУНАРОДНОЙ СИСТЕМОЙ КОНТРОЛЯ RIQAS

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АННОТАЦИЯ

В статье представлен анализ этапов развития биохимических исследований в ветеринарной лаборатории ТОО «Экви Лаб» – от ручных методов (с использованием спектрофотометра) до внедрения автоматических биохимических анализаторов. Особое внимание уделяется вопросам аналитической точности, получения достоверных результатов исследования *крови*.* Для этого проводятся обязательные мероприятия - ежедневные внутренние контроли (негативные и позитивные) и калибровка анализатора. Наряду с этим, для повышения качества биохимических исследований, подтверждения эффективности оборудования, был пройден внешний контроль точности измерения биохимических показателей по программе RIQAS (Randox International Quality Assessment Scheme), являющейся международным стандартом в лабораторной диагностике.

Ключевые слова: лабораторная диагностика крови мелких домашних животных (МДЖ), биохимический анализ, биохимический анализатор, внутренний контроль качества, внешний контроль качества, RIQAS.

ВВЕДЕНИЕ

Биологическая химия – наука о качественном составе и количественном содержании сложных природных соединений, из которых состоит живая материя, а также об их преобразовании в результате жизнедеятельности организма [1]. Кровь, как внутренняя среда, является специфическим индикатором состояния организма, и неотъемлемая часть доклинического исследования пациента – именно биохимический анализ крови. Он позволяет достаточно точно проанализировать состояние и органов, и систем организма, выявлять патологии, анализировать течение клинических процессов, оценивать эффективность лечения, качественно проводить профилактический скрининг. Простой пример: чтобы судить о тяжести патологического процесса в почках, необходимо определить - насколько в организме нарушено выделение продуктов обмена веществ из крови. Для этого определяют в крови мочевину, креатинин [1]. Учитывая, что для исследований берутся незначительные объёмы крови, очень важна безукоризненная точность в работе.

Цель данной работы – проследить этапы развития биохимических исследований в ветеринарной лаборатории ТОО «Экви Лаб», являющейся одной из первой, проложившей путь лабораторным диагностическим исследованиям мелких домашних животных в Казахстане.

МАТЕРИАЛЫ И МЕТОДЫ

Биохимические исследования крови МДЖ проводились в ветеринарной лаборатории ТОО «Экви Лаб». На разных этапах развития лабораторной диагностики использовались: спектрофотометр (для проведения ручного измерения веществ) Apel PD-303, Япония; полуавтоматический анализатор HTI Biochem SA, США; автоматические анализаторы HTI BioChem FC-120, США; автоматический анализатор Human, HumaStar 100, Германия. Внутренний контроль качества биохимических исследований проводился при помощи контрольных/калибровочных сывороток, рекомендованных производителем оборудования. Внешний контроль качества проведён международной системой RIQAS.
*для биохимических анализов используется *сыворотка крови.*

ЭТАПЫ РАЗВИТИЯ БИОХИМИЧЕСКИХ ИССЛЕДОВАНИЙ

С начала основания лаборатории ТОО «Экви Лаб» (2005 год) исследования биохимического состава крови проводились так называемым ***«ручным» методом*** с использованием спектрофотометра Apel PD-303, Япония. Прибор удобен своей универсальностью (открытая система позволяет использовать любые методики и реактивы), простотой настройки и управления (ручная настройка и установка длины волны, цифровой дисплей, на который выводятся прямые данные измерений), стабильностью показаний; диапазон волн 340-1000 нм; рекомендуемый объём пробы 1,0 мл [2]. Однако метод ручного измерения отличается низкой пропускной способностью, повышенным расходом реагентов, кроме того, значительное время занимает подготовка проб и оборудования персоналом, что, в свою очередь, усиливает так называемый «человеческий фактор» и, следовательно, вероятность ошибок.

В 2011 году на смену ручному методу в лабораторию пришел ***полуавтоматический биохимический анализатор*** HTI Biochem SA, США, в котором часть процессов автоматизирована (нагрев, измерение, расчеты, обработка и вывод результатов), а подготовка проб (смешивание реагентов и образцов) выполняется вручную. Этот анализатор является открытой системой (адаптируется к реагентам разных производителей), имеет встроенную проточную кювету, позволяющую экономить реагенты, термостатируемый блок на 10 ячеек; диапазон волн - 340-630 нм, обеспечивающий

выполнение большинства биохимических методик [3]. Полуавтоматический биохимический анализатор значительно выигрывает перед ручным методом в расходовании реагентов, в скорости исследований, в минимизации человеческого фактора, но проигрывает по тем же показателям автоматическим системам.

В 2018 году для повышения качества исследований Лаборатория ТОО «Экви Лаб» запустила в работу ***автоматический биохимический анализатор*** HTI BioChem FC-120, США, и стала первой в Казахстане, внедрившей автоматический анализатор в ветеринарную лабораторную практику. BioChem FC120 - компактный, настольный прибор с дизайном «все в одном» - встроенный компьютер, принтер, сенсорный экран, со свободно формируемым ротором - до 42 позиций для проб и до 26 позиций для реагентов, с производительностью 100 тестов в час, диапазоном волн - 340-670 нм; система реагентов - открытая [4]; обеспечивает высокую точность исследований с широким перечнем тестов; значительно сокращает время проведения анализов в сравнении с полуавтоматическими анализаторами, практически нивелирует человеческий фактор, так как проводит исследования без вмешательства оператора - необходимо лишь загрузить образцы и запустить прибор. Автоматический биохимический анализатор HTI BioChem FC-120 хорошо зарекомендовал себя в работе, поэтому для обеспечения дополнительной производительности лаборатории в 2020 году был приобретён такой же анализатор.

В 2024 году было принято решение обновления «парка» биохимических анализаторов автоматическим анализатором HumaStar 100, Human, Германия. Это анализатор открытого типа с производительностью 100 тестов в час, имеет 60 позиций для образцов и 30 позиций для реагентов, что позволяет длительное время работать без участия лаборанта; спектральный диапазон – 340-900 нм; возможно выполнение срочных анализов (программа STAT); в анализах используется низкий объём образца (2-300 мкл/тест), что повышает эффективность использования реагентов; имеет инновационное программное обеспечение, позволяющее интуитивно понятно управлять процессом, чему способствует внешний персональный компьютер. Анализатор оснащен 80 многоразовыми реакционными кюветами с 8-этапной системой автоматического промывания и достаточно низким потреблением воды (8 мл/тест или около 1 л/ч) [5].

При описании биохимических анализаторов мы не углублялись в технические характеристики приборов, а затронули лишь некоторые видимые «потребительские» преимущества или недостатки используемых нами анализаторов. На основании этого составлена нижеприведённая таблица.

Таблица 1. Сравнительная таблица методов биохимических исследований

№	Метод / биохимический анализатор	Название оборудования	Производи-тельность	Человеческий фактор
1	Ручной / спектрофотометр	Apel PD-303	Низкая	Высокий
2	Полуавтоматический	HTI Biochem SA	Средняя	Умеренный
3	Автоматический	HTI BioChem FC-120 Human, HumaStar 100	Высокая	Минимальный

Контроль качества

Контроль качества биохимических исследований – это регулярное осуществление системы мероприятий, которые выявляют и предотвращают недопустимые погрешности в

процессе выполнения лабораторных исследований, так как любые приборы не застрахованы от ошибок, любые реагенты требуют контроля. Поэтому оценка качества исследований – основа создания твердой уверенности в отсутствии аналитических ошибок, точности в работе оборудования и, следовательно, в достоверности полученных результатов.

Внутрилабораторный контроль качества.

Калибровка биохимических анализаторов – это крайне необходимая процедура, так как устанавливает соответствие между значениями оптической плотности и фактической концентрацией аналита в исследуемой пробе, обеспечивая надёжность и точность результатов. Колибровка в лаборатории выполняется специализированными растворами (калибраторы) с аттестованными значениями, которые приведены в прилагаемой к калибратору таблице. Калибровка проводится обязательно: по требованпию системы, после технического обслуживания, ремонта, смены лота реагентов, изменения внешней среды, но не реже одного раза в месяц, или согласно протоколу производителя. Валидация результатов – проведение контролей.

Ежедневно в лаборатории выполняется два уровня контроля биохимических исследований - *позитивный и негативный* [6]. Для этого используются сертифицированные контрольные материалы с заведомо известными величинами исследуемых аналитов в виде диапазона значений, которые приведены в прилагаемых к контролям таблицах. Величины, полученные в лаборатории, должны попасть в указанный диапазон.

Важно (!) при использовании калибровочного/контрольного материала четко следовать инструкции к выполняемой аналитической процедуре.

Внешний контроль качества – это система объективной оценки результатов исследований, проводимых в разных лабораториях мира, которые подтверждают, что методики различных лабораторий сравнимы между собой [6].

Так как лаборатория ТОО «ЭквиЛаб» ориентированна на обеспечение гарантированной достоверности анализов, в 2025 году было принято решение пройти международную оценку качества биохимических исследований через независимую внешнюю организацию RIQAS - Randox International Quality Assessment Scheme, Великобритания. В данной программе участвует более 50000 лабораторий из 139 стран мира. Лаборатория ТОО «Экви Лаб» на данный момент является единственной ветеринарной лабораторией в Казахстане, которая стала участником подобной программы. Внешний контроль качества лаборатория проходила анализатором HumaStar 100.

Перед началом проведения цикла проверки, лабораторией были получены запечатанные контрольные образцы («слепые пробы»), которые ежемесячно исследовались в период с апреля по декабрь 2025 года согласно предложенному графику. Результаты каждого исследования нами отправлялись на сайт компании, обрабатывались согласно регламенту, затем в виде отчетов анализа результатов поступали к нам [7]. Биохимический отдел лаборатории успешно справился с «расшифровкой» контрольных образцов, в результате чего был получен положительный итоговый отчет, и ТОО «Экви Лаб» удостоена «Certificate of Participation» от международной организации RIQAS. Такой итог стал несомненным подтверждением профессионализма сотрудников и надёжности результатов.

ЗАКЛЮЧЕНИЕ

Биохимические исследования крови являются неотъемлемой частью современной лабораторной диагностики, и играют ключевую роль в оценке функционального состояния органов и систем организма животного. Развитие технологий позволило существенно повысить точность, воспроизводимость и информативность получаемых результатов

исследований. На примере лаборатории ТОО «Экви Лаб» показана эволюция развития биохимических исследований в ветеринарной медицине Казахстана в целом.

Важным элементом получения достоверных результатов является многоуровневый контроль качества, которого лаборатория неукоснительно придерживается в своей работе. Это даёт основание утверждать, что лаборатория ТОО «Экви Лаб» является, бесспорно, надёжным проводником современных технологий в лабораторной практике и гарантом точности и надёжности проводимых измерений.

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Modern Imaging Methods for the Diagnosis of Legg–Calvé–Perthes Disease in Children: A Comparative Evaluation of the Diagnostic Capabilities of Radiography and Magnetic Resonance Imaging in Early Detection

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Abstract

Background. Legg–Calvé–Perthes disease (LCPD) is an idiopathic avascular necrosis of the femoral head in children. Its estimated incidence is approximately 1 case per 10,000 children, accounting for 0.25–0.5% of all pediatric orthopedic disorders [1, 2]. The disease most commonly affects children between 4 and 8 years of age, although it may occur between the ages of 2 and 15 years. It is significantly more common in boys than in girls, with a male-to-female ratio of approximately 4–5:1 [1, 2].Despite its relatively low incidence, delayed diagnosis and the absence of appropriate treatment may result in severe complications, including progressive deformity of the hip joint, functional impairment of the affected limb, and long-term disability. Therefore, early detection of the disease using modern imaging techniques, particularly radiography and magnetic resonance imaging (MRI), is of paramount importance for selecting the optimal treatment strategy and improving clinical outcomes.

Objective. To comparatively evaluate the diagnostic capabilities of radiography and magnetic resonance imaging (MRI) in the early diagnosis of Legg–Calvé–Perthes disease in children.

Objectives of the Study:

1. To review the fundamental principles of imaging diagnosis of Legg–Calvé–Perthes disease.
2. To analyze the diagnostic value of radiography for detecting Legg–Calvé–Perthes disease at different stages of the disease.
3. To investigate the role of magnetic resonance imaging in the early diagnosis of Legg–Calvé–Perthes disease and in assessing the extent of femoral head involvement.
4. To compare the diagnostic performance of radiography and magnetic resonance imaging in the early detection of Legg–Calvé–Perthes disease.
5. To identify the advantages and limitations of each imaging modality and to formulate recommendations for their rational use in clinical practice.

Materials and Methods

A comprehensive analysis, systematization, and synthesis of data from national and international scientific literature on contemporary imaging modalities for the diagnosis of Legg–Calvé–Perthes disease in children were performed. A comparative evaluation of the diagnostic capabilities of radiography and magnetic resonance imaging (MRI) for the early detection of the disease was conducted, together with an analysis of their respective advantages, limitations, and clinical significance.

Results
Radiography remains the primary diagnostic imaging modality due to its wide availability, low cost, and suitability for dynamic follow-up assessment. However, the sensitivity of radiography in the early stages of the disease is limited because pronounced structural changes are often absent.
Magnetic resonance imaging (MRI) enables the detection of early ischemic changes in the bone marrow, bone marrow edema, and impaired vascular supply of the femoral head before the appearance of radiographic signs of the disease. This significantly improves the effectiveness of early diagnosis.
Conclusion
The most rational approach is a comprehensive diagnostic strategy in which radiography is used as the first-line imaging modality, while magnetic resonance imaging (MRI) is performed in cases of persistent clinical suspicion of Legg–Calvé–Perthes disease despite the absence of radiographic abnormalities.
Keywords: Legg–Calvé–Perthes disease, children, imaging diagnosis, magnetic resonance imaging, radiography, early diagnosis, hip joint.

Introduction

Legg–Calvé–Perthes disease is one of the most common osteochondropathies of childhood and is characterized by the development of aseptic necrosis of the femoral head epiphysis resulting from impaired blood supply. The disease is most frequently diagnosed in children between 4 and 10 years of age and predominantly affects boys.

The clinical manifestations of the disease in its early stages are nonspecific and may include pain in the hip or knee joint, limping, and restricted range of motion. Therefore, imaging modalities play a crucial role in establishing an accurate diagnosis.

The prognosis of Legg–Calvé–Perthes disease is directly related to the timing of diagnosis and the prompt initiation of appropriate treatment; therefore, early detection remains a clinically relevant issue. For differential diagnosis, a comprehensive approach using various imaging modalities is recommended: radiography, ultrasonography, and magnetic resonance imaging (MRI) are primarily used in the early stages, whereas computed tomography (CT) may be applied at later stages of the disease.

In recent years, the role of magnetic resonance imaging has significantly increased due to its ability to detect pathological changes associated with the disease before the appearance of characteristic radiographic findings.

Results and Discussion

Radiography

Radiography remains the fundamental imaging modality for the evaluation of children with suspected Legg–Calvé–Perthes disease.

The main advantages of this method include:

- wide availability;
- low cost;
- rapid examination time;
- the possibility of dynamic follow-up monitoring.

Radiography also serves as the basis for applying international classification systems for Legg–Calvé–Perthes disease, which allow assessment of the extent of femoral head involvement, determination of disease prognosis, and selection of the optimal treatment strategy.

The **Salter–Thompson classification** is based on the detection of a subchondral fracture of the femoral head (the “crescent sign”) and includes two groups:

- **Group A** — the subchondral fracture line involves less than 50% of the epiphyseal surface; the prognosis is generally favorable.

- **Group B** — involvement of more than 50% of the epiphysis; the risk of deformity is significantly higher.

The **Herring classification (Lateral Pillar Classification)** is based on the assessment of the height of the lateral pillar of the femoral head epiphysis during the fragmentation stage:

- **Group A** — the lateral pillar is preserved, with no evidence of collapse or deformity.
- **Group B** — reduction in the height of the lateral pillar by less than 50%.
- **Group B/C** — an intermediate category between groups B and C.
- **Group C** — reduction in lateral pillar height by more than 50%, marked deformity, and an unfavorable prognosis.

The **Stulberg classification** is applied after skeletal maturity and allows assessment of disease outcomes based on the shape of the femoral head and the condition of the hip joint.

- **Class I** — normal joint morphology.
- **Class II** — nearly normal shape of the femoral head.
- **Class III** — spherical femoral head with increased size (*coxa magna*).
- **Class IV** — aspherical femoral head with moderate deformity.
- **Class V** — severe deformity of the femoral head and a high risk of early-onset coxarthrosis.

Classification	Basis of Assessment	Clinical Significance
Salter–Thompson	Subchondral fracture	Early assessment of the extent of necrosis
Herring (Lateral Pillar Classification)	Height of the lateral pillar	Selection of treatment strategy and prognosis
Stulberg	Femoral head shape after skeletal maturity	Evaluation of long-term outcomes and risk of coxarthrosis

In the early stage of the disease, radiographs may appear normal or may reveal only minimal widening of the joint space and slight enlargement of the epiphysis.

As the disease progresses, characteristic radiographic findings become apparent, including:

- areas of sclerosis;
- subchondral fracture;
- fragmentation of the femoral head;
- flattening of the epiphysis;
- deformity of the femoral head;
- signs of remodeling.

The main limitation of radiography is its low sensitivity during the pre-radiographic stage of the disease.

Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) is the most sensitive imaging modality for the diagnosis of early-stage Legg–Calvé–Perthes disease.

MRI enables visualization of:

- bone marrow edema;
- impaired blood supply to the epiphysis;
- areas of ischemia and early necrosis;
- the condition of articular cartilage;
- the presence of joint effusion;
- soft tissue abnormalities;

- the degree of femoral head perfusion;
- processes of revascularization and repair;
- potential disease complications.

MRI allows detection of pathological changes significantly earlier than the appearance of characteristic radiographic signs of the disease.

The use of T1-weighted, T2-weighted, and STIR sequences provides high diagnostic value and improves the accuracy of assessment of early pathological changes.

The main limitations of the method include:

- high cost;
- limited availability;
- the need for prolonged immobilization of the child during the examination;
- the possible requirement for sedation in younger children.

Comparative Characteristics of Imaging Methods

Criterion	Radiography	MRI
Availability	High	Moderate
Cost	Low	High
Radiation exposure	Present	Absent
Early-stage disease detection	Low	High
Assessment of bone marrow	Not possible	High
Visualization of soft tissues	Limited	Excellent
Treatment monitoring	Good	High
Examination duration	5–10 minutes	20–40 minutes

Diagnostic Algorithm

The modern diagnostic algorithm includes the following steps:

1. Clinical examination.
2. Radiography of the hip joints in two projections.
3. If radiographic abnormalities are absent but clinical suspicion of Legg–Calvé–Perthes disease persists, magnetic resonance imaging (MRI) should be performed.
4. Dynamic follow-up monitoring using radiography.
5. Repeat MRI when assessment of reparative processes is required.

Discussion

Current studies indicate that timely detection of Legg–Calvé–Perthes disease plays a crucial role in determining the effectiveness of subsequent treatment.

Despite the widespread use of radiography, magnetic resonance imaging (MRI) provides the earliest detection of the disease due to its ability to visualize ischemic changes in the bone marrow. This allows earlier initiation of joint unloading measures and conservative therapy, thereby reducing the risk of femoral head deformity.

However, the high cost of MRI and its limited availability prevent its use as a routine screening method.

Therefore, most specialists recommend a combined diagnostic approach in which radiography remains the first-line imaging modality, while MRI is reserved for equivocal cases or situations where clinical suspicion persists despite normal radiographic findings.

Conclusion

Radiography remains the primary imaging modality for the diagnosis of Legg–Calvé–Perthes disease due to its availability and ability to assess disease progression over time. However, its sensitivity during the early stages of the disease remains insufficient.

Magnetic resonance imaging (MRI) is the most informative method for early diagnosis, enabling detection of pathological changes before the development of radiographic abnormalities. The use of MRI significantly improves diagnostic accuracy and facilitates timely initiation of appropriate treatment.

The most effective diagnostic strategy is a rational combination of radiography and MRI, providing maximum diagnostic accuracy and optimization of therapeutic decision-making.

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ҚАЗАҚСТАНДАҒЫ АУЫЛШАРУШЫЛЫҒЫНА ЗАМАНАУИ ТЕХНОЛОГИЯЛАРДЫ ҚОЛДАНУ

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Аннотация: Бұл мақалада ауыл шаруашылығын цифрландыру – елдің әлеуметтік, экономикалық жағдайын жақсартудың ең тиімді жолы екені негізделінген. Сонымен қатар,әлемдегі ауыл шаруашылығы дәстүрлі саладан инновациялық шешімдер мен әзірлемелер үшін жаңа нарықтар құруға қабілетті жоғары технологиялық салаға айналуда екені көрсетілген.

Кілт сөздері: егін, егіс, алқаб,фермер,планшет, карта, агрономия, цифрлық, навигация, геоақпарат

КІРІСПЕ.

Қазіргі кезеңде ауыл шаруашылығының тиімділігі мен бәсекеге қабілеттілігі цифрлық технологияларды кеңінен енгізумен тікелей байланысты. Дүниежүзілік тәжірибе көрсеткендей, агроөнеркәсіптік кешеннің тұрақты дамуы инновациялық шешімдер мен интеллектуалды басқару жүйелерін пайдалануға негізделеді. Жер ресурстары шектеулі болғанымен жоғары өнімге қол жеткізіп отырған мемлекеттердің жетістігі дәл осы цифрлық және автоматтандырылған технологияларды тиімді қолданудың нәтижесі болып табылады.

Болашақ аграрлық сала мамандары өндірістік тәжірибелер барысында фермерлердің күнделікті жұмысын жеңілдетуге бағытталған цифрлық платформаларды әзірлеуде. Мұндай жүйелерде егістік алқаптарының электрондық карталары, топырақтың агрохимиялық көрсеткіштері, метеорологиялық мәліметтер, спутниктік бақылау нәтижелері, егіс құрылымы және басқа да маңызды ақпараттар бір ортада жинақталып, шаруашылықты басқару үдерісін оңтайландыруға мүмкіндік береді.

НЕГІЗГІ БӨЛІМ

Қазақстанда ауыл шаруашылығын цифрлық жаңғырту аясында GPS-навигациямен жабдықталған ауыл шаруашылығы техникалары, автоматты басқару жүйелері, электрондық алқап карталары, пилотсыз ұшу аппараттары және қашықтықтан мониторинг жүргізу технологиялары кезең-кезеңімен енгізілуде. Бұл құралдар өндірістік процестердің дәлдігін арттырып, еңбек өнімділігін жоғарылатуға және материалдық шығындарды азайтуға ықпал етеді [1].

Аграрлық сектордағы цифрландырудың маңызды бағыттарының бірі – дәл егіншілік технологиясы. Бұл жүйе әрбір егістік аумағының ерекшеліктерін ескере отырып, тыңайтқыштарды, суару көлемін және өсімдіктерді қорғау шараларын ғылыми негізде жоспарлауға мүмкіндік береді. Соның нәтижесінде табиғи ресурстар ұтымды пайдаланылып, өнім сапасы мен көлемі артады, ал қоршаған ортаға түсетін антропогендік әсер төмендейді.

Дәл егіншілікті жүзеге асыруда геоақпараттық жүйелер ерекше рөл атқарады. Олар электрондық карталар мен кеңістіктік деректерді өңдеу арқылы фермерлерге басқарушылық шешімдерді дәл қабылдауға жағдай жасайды. Сонымен қатар жоғары дәлдіктегі навигациялық жүйелер техниканың қозғалысын оңтайландырып, жанар-жағармай шығынын азайтады және далалық жұмыстардың сапасын арттырады.

Елімізде цифрлық технологияларды енгізу деңгейі барлық шаруашылықтарда бірдей емес. Ірі агроқұрылымдар қажетті қаржы мен техникалық мүмкіндіктердің арқасында заманауи технологияларды белсенді пайдаланып келеді. Ал шағын және орта шаруашылықтарда қаржылық шектеулер мен білікті мамандардың жетіспеушілігі цифрландырудың қарқынын баяулатуда. Сондықтан дәл егіншілік технологияларын тиімді пайдалану үшін материалдық-техникалық база мен кадрлық әлеуеттің жеткілікті болуы маңызды.

Бүгінде мобильді қосымшалар ауыл шаруашылығын басқарудың маңызды құралдарының біріне айналды. Олар арқылы ауа райының өзгерісін бақылауға, егістік алқаптарының жағдайын бағалауға, агротехникалық жұмыстарды жоспарлауға, қаржылық операцияларды жүргізуге және болашақ өнім көлеміне болжам жасауға болады. Мұндай цифрлық сервистер фермерлердің уақытын үнемдеп қана қоймай, басқару шешімдерінің тиімділігін де арттырады.

Алайда цифрлық технологиялардың барлық артықшылықтарын пайдалану үшін фермерлердің цифрлық сауаттылығын арттыру және оларды заманауи техникамен қамтамасыз ету қажет. Әсіресе шағын және орта ауыл шаруашылығы тауар өндірушілерін мемлекеттік қолдау маңызды. Бұл субсидиялар, жеңілдетілген несиелер, оқыту бағдарламалары және цифрлық платформаларға қолжетімділікті кеңейту арқылы жүзеге асырылуы мүмкін.

АҚШ, Канада, Бразилия және Австралия сияқты аграрлық салада көшбасшы елдердің тәжірибесі ауыл шаруашылығының табысты дамуы цифрлық инфрақұрылымның сапасына тәуелді екенін дәлелдейді [2].

Сондықтан отандық шаруашылықтар GPS-навигациямен жабдықталған техникаларды, интеллектуалды датчиктерді, спутниктік мониторинг жүйелерін және мобильді сервистерді кеңінен енгізумен қатар, сала мамандарының кәсіби біліктілігін тұрақты түрде жетілдіріп отыруы қажет. Осындай кешенді шаралар ғана ауыл шаруашылығы өндірісінің тиімділігін арттырып, еліміздің азық-түлік қауіпсіздігін қамтамасыз етуге және агроөнеркәсіптік кешеннің тұрақты дамуына негіз болады.

Ауыл шаруашылығында цифрлық технологияларды тиімді пайдалану табиғи-климаттық жағдайларды жан-жақты талдаудан басталады. Метеорологиялық мәліметтерді жүйелі түрде бақылау фермерлерге егіс және жинау жұмыстарын ғылыми негізде жоспарлауға, дақылдардың биологиялық ерекшеліктеріне сәйкес агротехникалық шараларды уақытылы орындауға және қолайлы сорттарды таңдауға мүмкіндік береді. Сонымен қатар ауа температурасы, жауын-шашын мөлшері, ылғалдылық пен жел жылдамдығы сияқты көрсеткіштер өсімдіктердің өсу кезеңдерін бағалауға және ықтимал тәуекелдерді алдын ала болжауға жағдай жасайды[3].

Қазіргі таңда дәл егіншілік технологияларының тиімді жұмыс істеуі электрондық картографиялық жүйелерсіз мүмкін емес. Геоақпараттық платформалар егістік алқаптарының шекарасын анықтап қана қоймай, топырақ құрамын, құнарлылық деңгейін, агрохимиялық көрсеткіштерді, өнімділік динамикасын және фитосанитарлық жағдайды бір деректер қорында сақтауға мүмкіндік береді. Осындай ақпараттарды кешенді талдау нәтижесінде тыңайтқыштарды енгізу, суару жүйесін ұйымдастыру және өсімдіктерді қорғау шаралары нақты қажеттілікке сәйкес жүзеге асырылады.

Цифрландырудың дамуы ауыл шаруашылығы өндірісін автоматтандырудың жаңа мүмкіндіктерін қалыптастырды. Заманауи сүт фермалары мен егіншілік кешендерінде интеллектуалды басқару жүйелері, датчиктер және автоматтандырылған бақылау құрылғылары кеңінен қолданылып келеді. GPS-навигациямен жабдықталған ауыл шаруашылығы техникалары егістік алқаптарында дәл қозғалып, тұқым себу, тыңайтқыш енгізу және химиялық өңдеу жұмыстарын жоғары дәлдікпен орындайды. Мұндай технологиялар жанар-жағармай шығынын азайтып, уақытты үнемдеуге және өндірістік шығындарды төмендетуге ықпал етеді[4].

Әлемдік тәжірибе көрсеткендей, цифрлық шешімдерді қолдану ауыл шаруашылығы өндірісінің тиімділігін едәуір арттырады. Мысалы, Бразилия, АҚШ, Канада, Израиль және Қытай сияқты мемлекеттерде спутниктік мониторинг, дрондар, жасанды интеллект және үлкен деректерді талдау жүйелері кеңінен енгізілген. Бұл технологиялар егістіктің жай-күйін жедел бағалап, өнімділікке әсер ететін факторларды нақты анықтауға және ресурстарды ұтымды пайдалануға мүмкіндік береді. Нәтижесінде өндірістік шығындар азайып, өнім көлемі мен сапасы артады.

Сонымен қатар аграрлық секторды цифрландыру тек жаңа техниканы енгізумен шектелмейді. Мәліметтерді жинау, сақтау, өңдеу және талдау әдістерін жетілдіру, ақпараттық қауіпсіздікті қамтамасыз ету және ғылыми зерттеулерді дамыту да ерекше маңызға ие. Сондықтан ауыл шаруашылығында цифрлық экожүйені қалыптастыру үшін заманауи бағдарламалық қамтамасыз ету, сенімді байланыс желілері және тиімді құқықтық реттеу тетіктері қатар дамытылуы қажет.

Қазақстанның агроөнеркәсіптік кешенінің халықаралық нарықтағы бәсекеге қабілеттілігі инновациялық технологияларды меңгерген кәсіби мамандардың даярлық деңгейіне тікелей байланысты. Сондықтан жоғары оқу орындары цифрлық агротехнологияларды, геоақпараттық жүйелерді, қашықтықтан зондтау әдістерін және деректерді интеллектуалды өңдеу құралдарын білім беру бағдарламаларына кеңінен енгізуде.

ҚОРЫТЫНДЫ

Қазіргі университеттерде жер және су ресурстарын тиімді пайдалану, топырақтың деградациясын төмендету, агроэкологиялық қауіпсіздікті сақтау және өндірістік процестерді автоматтандыру бағытында ғылыми-зерттеу жұмыстары қарқынды жүргізілуде. Студенттер зертханалық және өндірістік тәжірибелер барысында геоақпараттық жүйелермен, ұшқышсыз ұшу аппараттарымен, спутниктік суреттерді өңдеу бағдарламаларымен және цифрлық мониторинг құралдарымен жұмыс істеуді меңгереді. Бұл олардың теориялық білімін тәжірибемен ұштастырып, еңбек нарығында сұранысқа ие маман ретінде қалыптасуына мүмкіндік береді[5].

Болашақта ауыл шаруашылығы саласының тұрақты дамуы цифрлық трансформацияны кеңейтуге, ғылыми жаңалықтарды өндіріске енгізуге және жоғары білікті кадрларды даярлауға тәуелді болады. Осындай кешенді жұмыстардың нәтижесінде агроөнеркәсіп кешенінің тиімділігі артып, еліміздің азық-түлік қауіпсіздігі нығайып, ұлттық экономиканың орнықты дамуына елеулі үлес қосылады. серпін берері анық.

Қолданылған әдебиет:

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Economic Sciences

Efficiency, competition and credit risk in Madagascar's banking sector – a two-stage DEA-SBM-Malmquist analysis

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Abstract

This study analyzes the efficiency of commercial banks in Madagascar, as well as the effect of credit risk, competition, and the macroeconomic environment on their efficiency during the period 2010-2024. Our hypotheses were initially supported by the literature and also by the BFM survey of the banking sector. A two-stage approach was used, combining the SBM DEA double frontier method following Wang et al. (2007) and a second-stage regression estimated using wild bootstrap clusters. This methodological strategy allows for a rigorous measurement of efficiency while correcting for econometric problems. The empirical results highlight a negative effect of credit risk on banking efficiency, thus reducing operational performance. The Lerner index shows a positive effect, with the most efficient banks gaining market power and generating higher margins. Furthermore, economic growth has a positive effect on banking efficiency, and banks have generally been more resilient to COVID-19. Therefore, a favorable macroeconomic environment improves borrower creditworthiness, stimulates credit demand, and reduces payment defaults.

Keywords: Bank efficiency, Slack Based Measure Data Envelopment Analysis, Double frontier, Two stage DEA, Wild bootstrap.

1. Introduction

It is worth noting that in developing countries, the economy's financing relies primarily on financial intermediation. The relationship between the development of financial intermediation and economic growth has been of great interest to economists. Most research concludes that there are positive links between financial development and economic growth, in line with the findings of Goldsmith (1969), King and Levine (1993), Chen Hao (2006), and Pradhan (2018). Belinga, Zhou and Doumbe (2016) highlight that the literature presents three hypotheses regarding the direction of causality between FD (Financial Development) and EG (Economic Growth): *from a supply-side perspective*, the development of the financial and banking system drives economic growth; *from a demand-side perspective*, FD is seen as an automatic response, reacting *passively* to the growth process; *the bidirectional perspective* posits the existence of a long-term circular relationship.

In the literature, the indicators of financial intermediation development used vary depending on the authors; Demirgüç and Levine (2001), who are leading authors on the subject, used the following criteria: size, activity, and efficiency. The efficiency indicator can be relative or absolute. For relative efficiency, which is of interest here, there are measures specific to financial institutions (Lima P, 2012); the measure of efficiency aims to determine the extent to which banks provide an

optimal combination of financial services from a given set of inputs (Farrell, 1957). Let us assume that banks act rationally. That is to say, a bank operates in such a way as to pursue its own objectives in the best possible, optimal manner, all other things being equal. Of course, this implies that banks are assumed to understand the mechanisms of their own production and have the capacity and willingness to use them to achieve their objectives.

DEA data analysis is a non-parametric linear programming technique that extends the idea of estimating efficiency by comparing each decision-making unit. The DEA literature on banking efficiency is extensive. However, only a few studies have been conducted on the African continent (Henriques et al., 2020), primarily using the two-stage SBM-DEA model, which examines the relationship between credit risk, competition and banking efficiency. Most existing studies focus on major banking sectors or developed sectors, and relatively few apply two-stage DEA models to small banking systems or banking systems in developing countries, or do not take sufficient account of the influence of environmental factors, macroeconomic conditions or random errors, which may bias efficiency estimates.

Furthermore, in Madagascar, the banking sector is characterized by a highly concentrated market, in addition to a rather unstable economic climate, which, according to quarterly surveys conducted by the BFM (2024, 2025) on the banking sector, is slowing down the sector's development. In response to this gap in the literature regarding the use of the two-stage DEA method with Bootstrap in the banking sector in Africa, and particularly in Madagascar, this study seeks to answer the question: To what extent are banks operating in Madagascar efficient, taking their environments into account?

- Hypothesis (H1): Non-performing loans hurt a bank's performance
- Hypothesis (H2): The competitive structure of the banking sector has an impact on a bank's efficiency (negative, based on surveys conducted by the BFM)
- Hypothesis (H3): Macroeconomic conditions have an impact on a bank's efficiency.

This study contributes to the body of research seeking to understand the relationship between efficiency, competition and credit risk in a country where production and financial infrastructures are underdeveloped. The aim is to understand, verify and measure the factors limiting the development of the banking sector in the country, based on the results of surveys conducted by the BFM. This is intended to assist policymakers and supervisors in formulating appropriate sectoral policies so that the banking system can fully fulfil its role as a driver of economic growth. It should be noted that the role of the Central Bank of Madagascar is not only to supervise the granting of loans but also to ensure the country's financial stability, and, in theory, competition within the banking sector has an impact on the country's financial stability. This study adopts a two-stage methodological approach combining static and dynamic analysis. Firstly, banking efficiency is estimated using a non-radial DEA model of the Slack-Based Measure (SBM) type, whilst changes in productivity are analyzed using the Malmquist index and its decomposition into efficiency changes and technological changes. In the second stage, the determinants of efficiency are examined using an econometric regression with Bootstrap according to the wild bootstrap-t methodology of Cameron and Miller (2008).

This study confirms that credit risk management is a key driver of improved banking efficiency, whilst market power, measured by the Lerner index, and a favorable macroeconomic environment contribute positively to the performance of financial institutions. These results enrich the literature on banking efficiency by combining a rigorous methodological approach with an integrated analysis of microeconomic and macroeconomic dimensions.

The remainder of this paper is organized as follows: In Section 2, we provide a review of the literature concerning the link between. In Section 3, we present our methodology and the data sources used. The SBM DEA double-boundary model, the Malmquist index, etc. In Section 4, we present the results and discuss them.

2. Literature review

2.1. Production in the banking sector

It should be noted that banking efficiency refers to a bank's ability to use its resources to maximize its output (revenue) or minimize its inputs (costs), taking into account market conditions and input prices. In the empirical literature, the appropriate definition of output and the specification of inputs and outputs in the banking sector have been frequent topics of discussion. The technical efficiency of banks is measured using either the production approach or the intermediation approach. The former views banks as producers of services such as deposits and loans, with labor and capital as the main inputs. The latter views banks as agents responsible for transforming deposits and other funds into loans and other assets; it therefore considers banking inputs to consist of customer deposits and other market resources, as well as operating costs (Ferrier and Lovell, 1990). There is a consensus that the intermediation approach is particularly appropriate for the traditional function of financial institutions (Tan & Walheer, 2024). Furthermore, this approach is best suited to analyzing the efficiency of banks in developing countries, as it best reflects the intermediary role of banks—that is, mobilizing deposits and channeling them into loans and investments—and because of its ability to incorporate both operating costs and interest costs (Zhou & Yang, 2022). The production approach is often considered more appropriate for assessing the efficiency of bank branches rather than that of institutions as a whole, as it focuses on the operational aspects of banking services (Degl'Innocenti et al., 2017).

To overcome the problem of classifying deposits as inputs or outputs, a new approach has emerged, in line with the current focus on profitability, and concentrates primarily on operational results (profit-oriented approach). This approach treats revenues such as interest received and non-financial income as outputs, whilst cost components such as staff costs and interest paid (Drake et al., 2006) are inputs, to reduce costs and increase the bank's revenues. The most commonly used outputs are loans and income-generating assets, as shown by Casu and Molyneux (2003). However, it should be borne in mind that the efficiency of financial institutions entails improved profitability, increased mobilization of financial resources, better pricing, and improved quality of services offered to consumers in this competitive environment (Ullah S. et al. (2023).

With regard to research into other factors that determine the efficiency of banks, the factors influencing banking efficiency can be classified into microeconomic factors linked to the specific characteristics of banks and fundamental macroeconomic factors. Non-performing loans, insufficient capitalization, size and scale, the use of modern technologies[1], and staff training are the factors most frequently cited in the literature at the internal and micro levels (Kamgna et al., 2008; Dhouha et al., 2009; Matthews & Xiao, 2020), as opposed to macroeconomic factors (crises, economic cycles, inflation, etc.) and socio-legal factors. Higher levels of economic development are associated with increased banking sector efficiency (Opperman & Adjasi, 2019), and a stable macroeconomic environment with well-developed financial structures promotes banking efficiency, whilst volatility (e.g. volatility in remittances) is detrimental (Alandejani, 2022).

Regarding undercapitalisation2the authors' findings vary: Pasiouras et al. (2009) and Dell'Atti et al. (2015) have highlighted a negative relationship between capitalization and banking efficiency. According to the regulatory hypothesis, the existence of a regulatory authority encourages banks to be more efficient and better managed when their level of capitalization is relatively low. The fact that higher capital levels increase agency costs between management and shareholders by reducing the discipline imposed on management by debt repayment. Banks with moderate levels of capitalization would potentially be easier to manage and supervise in terms of credit quality,

[1] The underutilization of IT budgets has been identified as a source of inefficiency in some banks (Fukuyama et al., 2021)

thereby reducing information asymmetry and improving their efficiency. However, some authors (Marques-Ibanez and Molyneux, 2011; Pessarossi and Weill, 2015) note that banks with the highest levels of equity capital are more efficient.

2.2. Competition, credit risk and bank efficiency

The ES (Efficiency Structure) theory proposed by Demsetz (1974) and Peltzman (1997) asserts that the exceptional performance of market-leading firms (due to specific factors such as a high level of technology and management, etc.) will endogenously determine the market structure, meaning that greater efficiency can also lead to concentration and higher profits. In this sense, concentration reflects and rewards efficient banks, but does not necessarily imply an increase in market power. However, one must not overlook the fact that a monopoly situation can lead to lax behavior or a deviation from the objective of efficiency, which can be detrimental to society. It can be assumed that certain bank executives may take advantage of the lack of competition to incur unnecessary expenditure (construction of excessively expensive buildings, excessive salaries, bonuses, and other benefits, Dittus (2004), Bonin et al. (1998)). Standard economic theory, i.e. the Structure-Behaviour-Performance paradigm, predicts that high concentration in banking markets implies market power for banks, which raises the cost of credit and consequently curbs investment and business activity (Beck, Demirgüç-Kunt, and Maksimovic, 2004). Pierre J and Jean-Paul P (2012) noted that: 'the creation of monopoly positions can place banks in a position not only to recoup their investment in information, but also to overcharge (exploit) their borrowers. Having invested in a relationship that makes their customers captive (i.e., making it costly for them to switch to competitors), they can impose excessively stringent credit conditions". The Information Generating Hypothesis (IGH) developed by Marquez (2002) proposes a positive relationship between market power and bank efficiency. The IGH suggests that in the face of intense competition, bank managers are likely to be more interested in quantity than quality in order to gain a larger market share relative to their competitors, by expanding their asset portfolio even if this compromises asset quality.

Several authors have found that bank concentration is a necessary evil for banking efficiency and that it is not necessarily detrimental to economic activity [Demsetz (1973); Goddard, Molyneux, and Wilson (2004); Ion L., Emmanuelle N. (2011)]. Indeed, in the banking industry, productive efficiency is achieved either by seeking economies of scale or through economies of scope (risk diversification and liquidity). Theoretically, this is explained by the role of banks, which is to reduce information asymmetry: faced with competitive pressures, and thus a narrowing of their interest margin, banks do not undertake monitoring for the selection or tracking of projects. Eber N. (2000), within Sussman's (1993) framework of spatial competition, found that an efficient banking system should be characterized by a high concentration of the credit market (reducing information costs) without this high concentration acting as a significant obstacle to investment and economic activity, as can be observed in Germany or Japan.

The findings of Osei-Tutu and Weill (2022) show that banking efficiency has a positive impact on access to credit and that gains in banking efficiency help to alleviate credit constraints for firms when the macroeconomic environment is more developed and stable.

Berger et al. (1997) found that there is a negative relationship between cost efficiency and risk in distressed banks. They offered several explanations for this finding. Firstly, inefficient banks, in addition to having problems controlling their internal costs, may encounter difficulties in assessing credit risk, so that poor cost management goes hand in hand with higher credit risk, known as the 'mismanagement hypothesis'. Secondly, bad loans may arise due to adverse economic circumstances beyond the banks' control, meaning that banks must devote more resources to recovering non-performing loans, the 'bad luck hypothesis'.

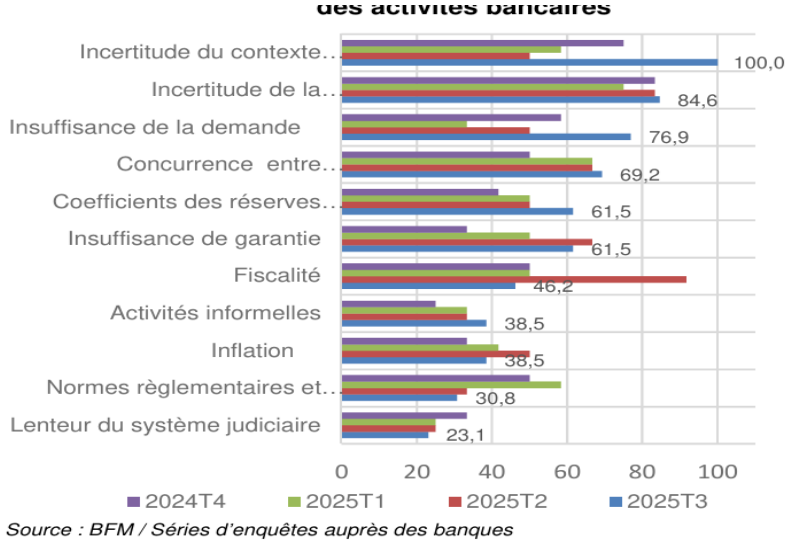
The significance of banks' non-performing loans for economic growth lies in the fact that a higher NPA influences loan prices and interest rates. Higher interest rates, in turn, will have a direct

impact on investors requiring loans for infrastructure and industrial projects (Bernanke & Gertler, 1989; Nkusu, 2011; Klein, 2013).

2.3. The banking sector in Madagascar

As already mentioned, there is little research that has examined the efficiency of the country's banking system, particularly at the microeconomic level. According to Razafindravonona et al. (2020), levels of non-performing loans (NPLs) in the Malagasy banking sector rise significantly during macroeconomic shocks such as a contraction in GDP or a depreciation of the exchange rate. The results show that NPLs can rise by nearly 3 percentage points under an adverse scenario. However, banks remain sufficiently capitalized, liquid and profitable (IMF, 2023). In 2024, Madagascar had 16 banks. Most of these are foreign banks, which are commercial banks and, according to the literature, are expected to be more efficient due to their technological and managerial advances. Their primary focus is therefore on shareholder profitability, which limits financing for long-term and risky projects in the country. Although Leightner and Lovell (1998) argue that opening up banks to foreign capital in emerging economies improves their performance by providing them with greater access to technology and, above all, to best governance practices. The banking sector is essentially risk-averse and relies primarily on asset-backed loans (World Bank, 2014). The cost of borrowing in Madagascar, at 48.86%, does not align with the sub-Saharan African average of 11%. Imperfect competition in the banking sector in Madagascar limits the decline in the interest margin to 8.8% (Financial Structure Dataset, 2019). The low level of banking penetration among the population, combined with uncertain economic conditions, leads to a preference for cash. The increase in the M1 aggregate during periods of uncertainty illustrates this preference. Another reason is that banks hold excess liquidity on their balance sheets because demand for credit from non-financial economic agents is low or is considered ris ly (the non-performing loan ratio stood at 7.7% in June 2024 according to the World Bank's economic update), placing the country 12th in Africa for NPLs (non-performing loans). As Mishkin F. (2013) points out, due to information asymmetry and the highly risky business environment, banks may accumulate liquidity because they prefer to keep it on their books rather than grant loans to non-financial economic agents deemed risky. The use of assets to secure loans may not be reliable due to uncertainties in the judicial system and contract enforcement. *The Fraser Institute*'s Property Rights Index stood at 3.02 in 2017 and remained at 117th place globally in 2025, indicating weak contract protection and enforcement.

Figure 1 Factors hindering the development of the banking sector in Madagascar, according to the banks



Source : BFM / Séries d'enquêtes auprès des banques

3. Methodology and data

3.1. Description of the double-boundary SBM-DEA model and first stage

Banking efficiency is generally measured using two main approaches: parametric and non-parametric methods. The most widely used parametric method is stochastic frontier analysis (SFA), whilst the most common non-parametric method is data envelopment analysis (DEA). DEA is a non-parametric linear mathematical programming technique whose objective is to analyze a group of homogeneous production units known as decision-making units (DMUs) that share the same inputs and outputs, to identify the most efficient organizations and indicate the actions that inefficient organizations must take to become efficient. The assumption is that if a producer J is capable of producing yJ with xJ , then other producers are also capable of doing the same if they are efficient. Thus, producer J and the others can be combined to form what we might call a virtual producer with composite inputs and outputs. The core of the analysis involves finding the best virtual producer for each real producer (Dovis, 2009).

The DEA method does not require the specification of a functional form regarding the type of production frontier, as the data envelope curve is constructed by selecting several efficient decision-making units. There are numerous modelling methods for assessing efficiency in DEA; the traditional models are CCR (Charnes, Cooper, Rhodes with constant returns to scale) and BCC (Banker, Charnes, Cooper with variable returns to scale), which are radial approaches, assuming that all inputs and outputs vary proportionally. The strengths of DEA include, in particular, its effectiveness in handling complex production processes (Schaffnit, Rosen, & Paradi, 1997); its ability to work with inputs and outputs on different scales of measurement (Svitalkova, 2014); its ability to analyse each DMU individually, comparing them with other DMUs, with the optimization process being carried out for all DMUs in the sample (Repková, 2014); and its ability to identify inefficient DMUs. However, it should be noted that the number of DMUs must be at least three times greater; otherwise, many DMUs will be considered efficient (Cooper, Seiford, Tone et al., 2007).

The SBM (Slacks-Based Measure) efficiency measurement method introduced by the Japanese researcher Tone (1997, 2001) is a non-radial efficiency measure within the DEA efficiency measurement method. Its advantage is that it directly measures excess inputs and underproduction. The distance between inputs and outputs relative to the production frontier is called the slack, and is used to measure efficiency. It allows for differentiated adjustments for each input and output and is therefore more realistic. The model below is taken from the work of Cooper, Seiford, Tone et al (2007).

To measure the efficiency of banks, let us assume we have $x^t \in R^m$ and $y^t \in R^s$, which are the selected inputs (m) and outputs (s), and n is the number of banks.

The production function is given by

$P^t = \{(x^t, y^t): x^t can\ product\ y^t\}$ (1)

Estimate the efficiency of a DMU (x_o, y_o) , we formulate the following fractional program in λ, s^- and $\boldsymbol{s}^+$: (SBM)

$$\min_{\lambda, s^-, s^+} \rho^{opt} = \frac{1-\frac{1}{m}\sum_{i-1}^{m}\frac{s_i^-}{x_{io}}}{1+\frac{1}{s}\sum_{r-1}^{s}\frac{s_r^+}{y_{ro}}} \quad (2)$$

Subject to the constraints:

$$x_o = X\lambda + s^-$$
$$y_o = Y\lambda - s^+$$
$$\lambda \geq 0, s^- \geq 0, s^+ \geq 0$$

In this model, $s^-$and $\boldsymbol{s}^+$ are the input and output slacks; we assume that $X \geq 0$. It is also easy to verify that an increase in s_i^-or s_r^+, ll other things being equal, decreases the value of the objective function in a strictly monotonically decreasing manner. ρ represents the ratios of the average combination inefficiencies of inputs and outputs, with the upper bound, ρ = 1, being reached only

if the slacks are zero for all inputs and all outputs. Therefore, a DMU ($\boldsymbol{x}_o, \boldsymbol{y}_o$) is SBM-efficient if and only if $\rho^* = 1$, and $\boldsymbol{s}^{-*} = 0$ and $\boldsymbol{s}^{+*} = 0$

$$0 \leq \rho \leq 1. \text{ (3)}$$

Since $s_i^- \leq x_{io}$ for all i , so that, with only if the data show that no quantity of that input was required. For outputs, an output shortfall represented by a non-zero slack may exceed the quantity of output actually produced.

ρ in can be transformed into

$$= \left(\frac{1}{m}\sum_{i=1}^{m} \frac{x_{io}-s_i^-}{x_{io}}\right)\left(\frac{1}{s}\sum_{r=1}^{S} \frac{y_{ro}+s_r^+}{y_{ro}}\right)^{-1} \text{(4)}$$

The ratio evaluates the relative rate of reduction of input i and, consequently, the first term corresponds to the average rate of proportional reduction of inputs, or to the inefficiencies in the combination of inputs. Similarly, the ratio evaluates the relative rate of proportional expansion of output r. That is to say, the second term measures the inefficiency in the combination of outputs. For an SBM-inefficient DMU ($\boldsymbol{x}_o, \boldsymbol{y}_o$), we have the expression:

$$\boldsymbol{x}_o = X\lambda^* + \boldsymbol{s}^{-*}$$
$$\boldsymbol{y}_o = Y\lambda^* - \boldsymbol{s}^{+*}$$

The SBM score ρ∗ can be broken down as follows:

$$\rho^* = \frac{1-\sum_{i=1}^{m} \alpha_i}{1+\sum_{r=1}^{S} \beta_r}$$

$$\text{où} \quad \alpha_i = \frac{1}{m}\frac{s_i^{-*}}{x_{io}} (i = 1, \dots, m) \text{ (5)}$$

$$\beta_r = \frac{1}{s}\frac{s_r^{+*}}{y_{ro}} \cdot (r = 1, \dots, s)$$

Decomposition is important for assessing the sources and extent of inefficiency associated with the various inputs and outputs of the DMU. In the model above, therefore, a DMU with a score close to 1 is **efficient in the optimistic sense** if it is deemed **inefficient in the optimistic sense.**

However, it is also possible to measure the **'pessimistic'** efficiency of banks. In particular, an inefficient frontier (or 'worst practice') can be estimated. Banks furthest from this inefficient frontier are considered more efficient (Wang and Chin, 2009). The higher the pessimistic score, the better the bank's performance; **a score of 1 indicates that the bank is on the frontier and is therefore among the least efficient.**

The pessimistic SBM DEA model according to Liu & Chen (2009) can be expressed as follows:

$$\max \rho^{pes} = \frac{1+\frac{1}{m}\sum_{i=1}^{m} \frac{s_i}{x_{io}}}{1-\frac{1}{s}\sum_{r=1}^{S} \frac{s_r}{y_{ro}}} \text{ (6)}$$

Subject to the constraint:

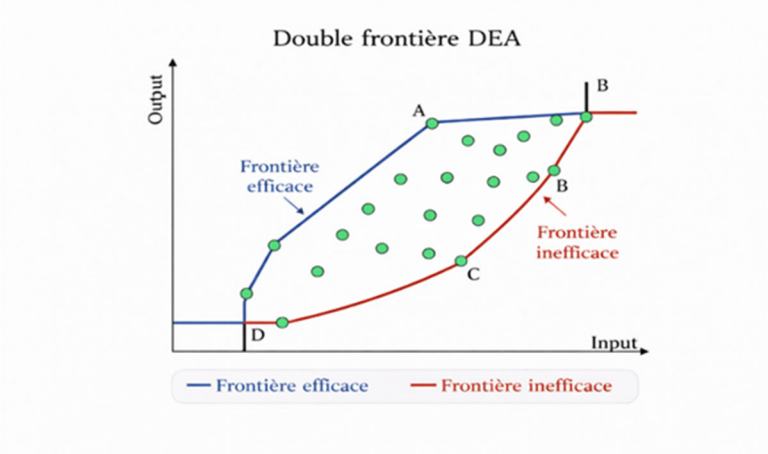
$$x_o = X\lambda - s^+$$
$$y_o = Y\lambda + s^-$$
$$\lambda \geq 0, s^+ \geq 0, s^- \geq 0$$
$$\rho \geq 1$$

Here we have two frontiers, an optimistic and a pessimistic one; we can follow Wang et al. ((2007) to calculate the overall efficiency of bank j in year t as the geometric mean of using the equation below. Both frontiers must be considered simultaneously in the efficiency analysis in order to obtain better estimates, Liu & Chen (2009). The higher the value of ρ^{all} , the better the bank's performance.

$$\rho^{all} = \sqrt{\rho_{j,t}^{opt} \times \rho_{j,t}^{pes}} \text{ (7)}$$

As already discussed in the section above, the profit-based approach resolves the issue of whether to treat deposits as inputs or outputs; consequently, the profit-based approach will be our choice for this study. Regarding inputs and outputs, we will use operating expenses as a proxy for expenditure on staff and physical capital. Interest expenses will be used as a proxy for expenditure on deposits and other creditors of the bank. As an output, we will choose operating profit as it allows us to include provisions for bad debts, and prevents banks from being deemed efficient without taking into account the risks they take. The models will be VRS, which takes into account economies of scale in the calculation of efficiency; this is widely used in studies of the banking sector as banks require economies of scale to operate.

Figure 2 Double-boundary DEA



Source : Authors, 2026

3.2. DEA-Malmquist index model

The DEA-Malmquist index method is used to analyze and decompose efficiency (Cooper, Seiford, Tone et al, 2007). All traditional DEA models use data from a specific year as a sample for analysis, which can only reflect the relative efficiency values of different economies at a single point in time, and does not allow for the study of changes in their efficiency across different periods. The DEA-Malmquist index model can measure dynamic changes in the efficiency of decision-making units using the 'directional distance function (DDF); it can therefore analyze panel data, which not only allows the total factor efficiency to be decomposed into technical efficiency, technological progress and scale efficiency, but also clarifies the reasons for changes in the total factor productivity of the subject under study.

The production frontier with an output-oriented distance function, under the assumption of constant returns to scale (CRS), can be defined as:

Technical efficiency is estimated relative to the production frontier, such that $0 < D_o^t(x^t, y^t) \leq 1$

The Malmquist productivity index must be defined on the basis of the reference technology, under CRS (constant returns to scale), and is:

$$M_t(x^t, y^t, x^{t+1}, y^{t+1}) = \frac{D_c^t(x^{t+1}, y^{t+1})}{D_c^t(x^t, y^t)}$$
$$M_{t+1}(x^t, y^t, x^{t+1}, y^{t+1}) = \frac{D_c^{t+1}(x^{t+1}, y^{t+1})}{D_c^{t+1}(x^t, y^t)} \quad (8)$$

Given that the Malmquist productivity indices defined by reference techniques based on the periods and are symmetric in economic terms, their geometric means are defined as composite productivity indices according to Fisher's concept, namely:

$$TFP = EFFCH \times TECHCH \quad (9)$$

There is no difference between the and TECHCH (boundary shift) indices with regard to the Malmquist productivity index itself. The EFFCH ratio measures the change in a DMU's technical efficiency relative to the best-practice frontier, indicating whether it is moving closer to or further

away from the production frontier t and $t+1$; the difference between and lies in the decomposition of the index. EFFCH is then decomposed, as suggested by Färe et al. (1994), into changes in pure efficiency (PECH) and changes in scale efficiency (SECH).
The decomposition is as follows:

$$FFCH = PECH \times SECH$$

$$TFP = \frac{D_c^{t+1}(x^{t+1},y^{t+1})}{D_c^t(x^t,y^t)}$$

$$= \frac{D_c^{t+1}(x^{t+1},y^{t+1})}{D_v^{t+1}(x^{t+1},y^{t+1})} \times \frac{D_v^{t+1}(x^{t+1},y^{t+1})}{D_v^t(x^t,y^t)} \times \frac{D_v^t(x^t,y^t)}{D_c^t(x^t,y^t)} \quad (10)$$

$$= PECH \times SECH \times TECHCH$$

3.3. Two-stage DEA and bootstrapping

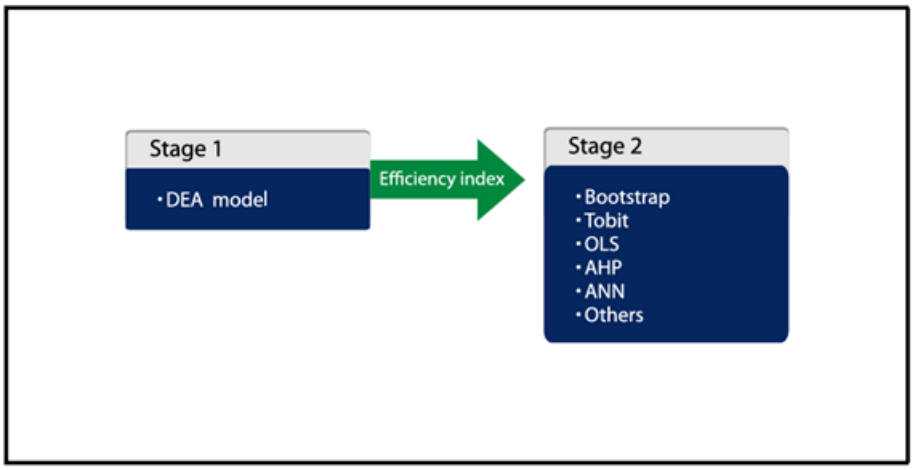
Two-stage DEA is widely used in studies of banking efficiency to estimate efficiency scores and explain their variation using environmental variables. This approach divides the analysis into two distinct phases: (1) the estimation of efficiency scores using DEA, and (2) the regression (or another technique, whether parametric or non-parametric) of these scores on environmental or contextual variables to identify their determinants and thus enable a more comprehensive analysis, Ayadi et al. (2016).
Traditional DEA models have been criticized for failing to take into account external environmental factors beyond the organization's control, over which decision-makers have no influence. In other words, the environment in which the bank operates is not considered in the analysis. Often, a bank is considered efficient (or inefficient) simply because it is aided by favorable external factors (or, conversely, suffers from unfavorable ones). This renders the efficiency scores of the DEA model biased.

In an effort to improve the application of DEA, two-stage DEA models have gained prominence in the literature, precisely because they help to overcome the aforementioned limitations. The econometric methods used in the second stage of two-stage DEA models are the subject of ongoing debate. Whilst Tobit regression is widely used due to the bounded nature of DEA scores, it is criticized for its lack of statistical consistency. Simar and Wilson (2007) developed a bootstrap-based truncated regression approach to address the limitations of conventional methods. They argue that DEA efficiency scores are biased and serially correlated, thereby invalidating standard inference in second-stage regressions. Given that the variables used as inputs are considered endogenous (Lensink & Meesters, 2014), the use of bias-corrected estimates in a stochastic framework offers additional protection against the classic endogeneity problems frequently encountered in regression specifications incorporating firm-level data (Van Biesebroeck, 2008). The bootstrap procedure is used to correct for bias and provide valid confidence intervals and standard errors, overcoming the problems of serial correlation and dependence inherent in DEA scores (Voltes-Dorta, Britto and Wilson, 2024).
In our case, the number of observations is quite small, but to correct for the effects of intra-bank relationships by year (data are often correlated within groups (clusters)). We will use the Bootstrap procedure of Cameron and Miller (2008), who demonstrated the effectiveness of the Wild Cluster Bootstrap-t [2]when dealing with clusters of 5–30. This method has the advantage, compared to other cluster-handling methods that estimate standard errors under the assumption of i.i.d., of being robust to heteroscedasticity and working with a small number of clusters. In standard clustering methods, the explanatory variables and the dependent variable must take on several

[2] See also Roodman et al (2019) for STATA

different values. **Wild cluster bootstrap** methods do not encounter this problem, as they do not resample the explanatory variables.

Figure 3 External two-stage DEA



Source: I.C. Henriques et al (2020)

The model used is presented as follows: *Eff* represents the wild cluster bootstrap bias-corrected efficiency scores of bank i at period t, Xit is a vector of bank-specific financial variables, Yit are the macroeconomic control variables, and εit is the error term.

Cap is defined as the ratio of equity to total assets, and is used to measure the strength of a bank's capital; it acts as a safety net for banks. **Credit risk (NPL)** is measured by the ratio of loan loss provisions to total loans. We therefore expect a negative relationship between credit risk and the level of banking efficiency. To account for economies of scale, we include the **size** variable, measured by the logarithm of banks' real total assets. As stated above, a larger size can reduce the costs of information asymmetry and information gathering. Following the study by Ziadi Ellouze (2024), **the ILer** (Lerner index) allows, amongst other things, the capture of the bank's market power effect. **(GDPg)** is introduced to control for the macroeconomic environment, Benbachir (2025). This variable is expected to be positively associated with levels of banking efficiency. Finally, our specifications take into account the effects of inflation. An instrumental variable for the Covid crisis (in 2020 and 2021) will be used to account for the effect of the health crisis on banks, given that they were the institutions most called upon by the government during the crisis, as well as to isolate the effect on economic growth and non-performing loans.

$$Eff_{it} = c + a'X'_{it} + \text{Criscov}_{it} + \gamma ILer'_{it} + \beta'Y'_{it} + \varepsilon_{it} \quad (11)$$

3.4. Lerner index

The Lerner index measures the degree of market power of a specific bank on an annual basis. It can be calculated using the relative difference between price and marginal cost. The Lerner index generally ranges from 0 to 1, with higher values indicating a higher level of market power and a lower level of competition, whilst lower values indicate a lower level of market power and a higher degree of competition (Fare et al., 2015; Fungacova et al., 2013; Tan & Floros, 2014; Tan et al., 2017; Liu et al., 2018). In some cases, the value of the Lerner index may be negative. We use the ordinary least squares method to estimate the Lerner index whilst controlling for bank fixed effects and time dummies. The specification can be expressed as follows:

$$\ln \text{Cost}_{it} = \beta_0 + \beta_1 \ln Q_{it} + \beta_2/2(\ln Q_{it})^2 + \sum \gamma_{kt} \ln P_{k,it} + \sum \varphi_k \ln Q_{it} \ln P_{k,it} + \sum \sum \delta_{kj} \ln P_{k,it} \ln P_{j,it} + \varepsilon_{it} \quad (12)$$

where ln denotes the natural logarithm, **Cost** denotes total cost, and **Q** denotes bank output. Here, the sum of interest income, non-interest income and net income serves as a proxy for bank output. P denotes the three input prices, PL, PF and PC are respectively: normally, labour cost is given by the ratio of staff costs to total assets. PL refers to human input, and we use operating expenses and total assets to proxy for PL and PK, as it is difficult to obtain complete data on staff costs and wages; since it is difficult to obtain the total number of staff, we draw here on the approach of Claessens and Laeven (2003) and Bikker and Haaf (2002). Cost of funds calculated as the ratio of interest expenses to total deposits. Following the approach of many other studies [Koetter et al. (2012); Shaffer et al. (2020)], we impose linear homogeneity in factor prices by normalizing total costs and factor prices relative to the cost of funds (PF).

The above equation is differentiated to derive the marginal cost with respect to output Q as follows

$$MC_{TA,it} = \frac{\text{Cost}_{it}}{Q_{it}[\beta_1+\beta_2 \ln Q_{it}+\sum \varphi_k \ln P_{k,it}]} \quad (13)$$

The Lerner index is given by:

$$\text{Lerner}_{it} = \left(P_{TA,it} - MC_{TA,it}\right)/P_{TA,it} \quad (14)$$

Where P represents the price, which is measured as the ratio of total revenue to total assets. MC represents marginal cost, and TA represents total assets. In certain scenarios, when the Lerner index is negative, the price level is lower than the marginal cost. This can be explained by the banking industry, which is characterized by a particularly high level of government subsidies. A negative Lerner index is beneficial to the banking industry, on the one hand because a higher marginal cost deters entry, which is conducive to improving the profits of existing banks. On the other hand, a marginal cost higher than the price level indicates that banks are incurring short-term losses. The results of the OLS regression for the Lerner index are presented in the table.

3.5. Data and software

In this study, we use data from the World Development Indicators (WDI) for macroeconomic variables, whilst the financial variables for each bank are drawn from the banks' annual reports. The observation period is 2012–2024, and the sample comprises five banks (BOA MADA, BNI, SG MADA, BMOI MADA, MCB MADA), which hold 90 per cent of the market share in the country (according to theglobaleconomy.com and madagascarinvest, 2025); we encountered difficulties in collecting data for the other banks in the sector. We used RStudio 2024.12 with R 4.5.2 for score calculations and econometric regression. The main package used for R in the calculation of scores was rDEA.

Table1 List of variables and data sources

variables	Source
Inflation rate	WDI World Bank
Economic growth	World Bank WDI
Bank financial variables	Banks' annual financial reports

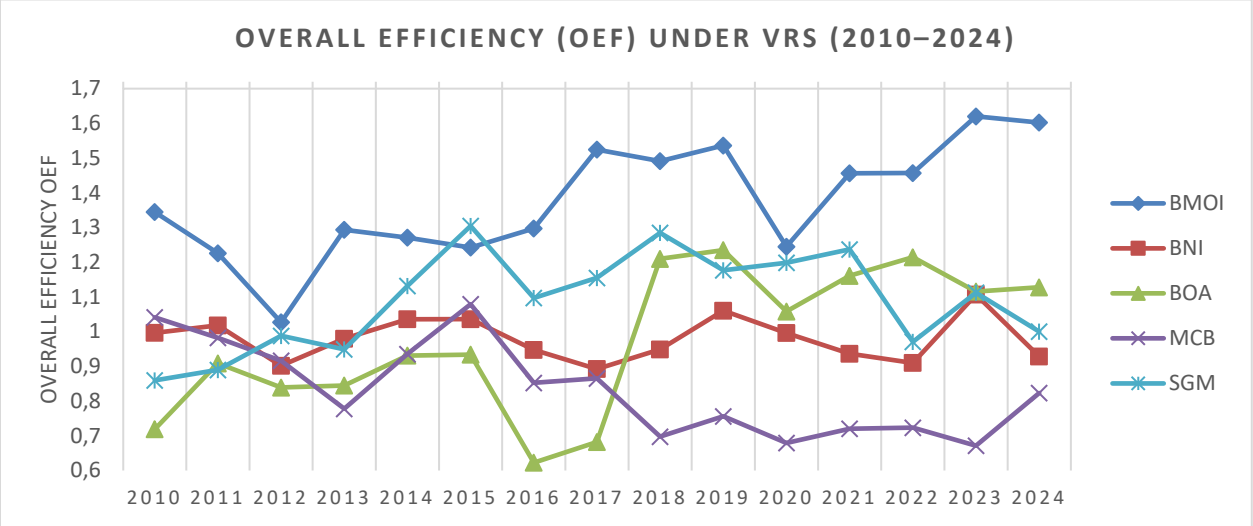
Source: Author, 2025

4. Results and discussion

4.1. Double-boundary DEA scores

In Table 4.1 of the Appendix, we first present the efficiency scores for the optimistic and pessimistic frontiers, as well as the geometric mean for the banks. As the table shows, the scores between the two frontiers differ but are consistent; using the average of the two frontiers allows for a better distinction between the banks that are efficient. If we examine the banks' average double-boundary score, BMOI is the most efficient with an average of 1.375 for the entire study period 2010–2024, followed by SGM with 1.09 and BNI, which rounds off the top three with 0.979. This result comes as little surprise, as BMOI is a bank whose client base consists mainly of corporate clients, so it performs better in terms of profit optimization. SGM (which became BRED Madagascar in 2024) and BNI are among the largest and oldest banks in the sector. Regarding the consistency of average scores over the period. We note that there is not much difference between the efficiency of the top-ranked bank and the bottom-ranked one; indeed, MCB, which has a score of 0.834 over the period, is less than 1.6 times the score of BMOI.

Figure 4: Estimation of dual-boundary VRS efficiencies



Source: Author's calculation using rDEA, 2025

It should also be noted that the banks experienced a decline in efficiency in 2020, which may be attributable to the COVID-19 crisis. Only SGM remained resilient in the face of the crisis, as shown in the graph above, though this resulted in a decline in efficiency in 2022. During the crisis, banks were heavily relied upon by the country's government, as was the case in most countries at that time. The increase in provisions for non-performing loans and loan restructuring, combined with the decline in activity, explains this drop in efficiency during the COVID-19 pandemic, as we will see in the sub-section below.

4.2. DEA Malmquist

As mentioned above, the DEA-MI allows us to measure changes in banks' total productivity in a dynamic manner. These changes are measured relative to changes in efficiency and technical progress. The table below shows the change in total productivity, the change in efficiency, the change in technology, pure efficiency, and scale efficiency, all on a five-year basis. The results by year/bank can be found in the appendix. It should be noted that the change in TFPCH is the product of EFFCH and TECHCH. We observe that banks' TFP is declining across the three sub-periods, although some banks show a higher rate of change in the 2015–2020 sub-period, i.e. prior to the COVID-19 crisis. It is clear that the change in TFP is really due to the change in TECHCH rather than EFFCH; for example, for BNI in 2015–2020, we see a 4.1% improvement in technical progress, which improves TFP by 1.5%; the 4.2% improvement in MCB over the same period allowed TFP to remain more or less stable; and finally, for SGM, a 6.3% increase in TECHCH resulted in a 2.2% rise in TFP. Thus, the crisis, which was expected to be a catalyst for digital transformation and

innovation, actually slowed technical progress due to recruitment freezes and budget cuts in the banking sector during the crisis; however, we now see that recruitment of IT staff is very much on the rise. The pure efficiency of banks is relatively stable, but the efficiency of scale shows that most banks, excluding BMOI, are not operating at their best or are failing to manage their growth to exploit economies of scale.

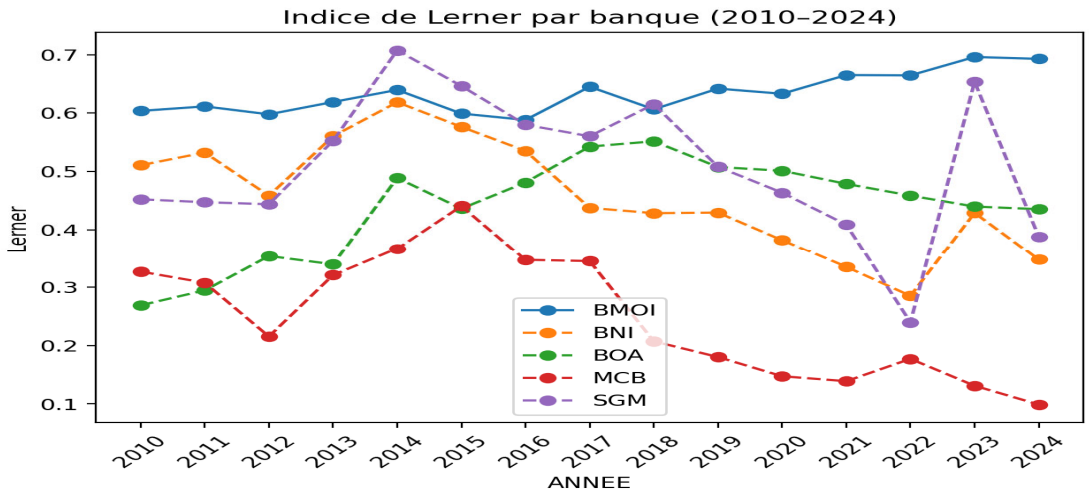
Table 2 Breakdown of the Malmquist index

Banque	Periode	TFPCH_geom	EFFCH_geom	TECHCH_geom	PECH_geom	SECH_geom
BMOI	2010-2015	1.0165020	0.9996077	1.0169010	1.0000000	0.9996077
BMOI	2015-2020	0.9810347	1.0003925	0.9806498	1.0000000	1.0003925
BMOI	2020-2024	0.9318339	1.0000000	0.9318339	1.0000000	1.0000000
BNI	2010-2015	0.9897152	1.0001894	0.9895277	0.9644218	1.0370871
BNI	2015-2020	1.0156731	0.9754811	1.0412022	1.0103689	0.9654703
BNI	2020-2024	0.9318495	0.9705026	0.9601720	1.0037614	0.9668659
BOA	2010-2015	1.0125491	1.0409599	0.9727071	0.9921208	1.0492270
BOA	2015-2020	0.9977965	0.9976976	1.0000991	1.0220888	0.9761359
BOA	2020-2024	0.9396514	0.9868217	0.9521997	1.0279545	0.9599858
MCB	2010-2015	0.9879468	0.9909893	0.9969298	1.0000000	0.9909893
MCB	2015-2020	0.9587389	0.9196819	1.0424680	1.0000000	0.9196819
MCB	2020-2024	0.9534369	1.0159891	0.9384321	1.0000000	1.0159891
SGM	2010-2015	1.0047129	1.0681807	0.9405833	1.0065424	1.0612376
SGM	2015-2020	1.0220462	0.9609295	1.0636017	1.0000000	0.9609295
SGM	2020-2024	0.9075726	0.9314618	0.9743530	1.0000000	0.9314618

Source: Author's calculation using rDEA, 2025

4.3. The Lerner index

Descriptive analysis results indicate that the banking sector exhibits significant market power over the period 2010–2024. The values of the Lerner index, mostly ranging between 0.4 and 0.7 (see appendix), suggest an oligopolistic structure rather than a perfectly competitive environment. Thus, BMOI has the most stable and highest Lerner index value, meaning that it sells its products with a higher margin over its marginal cost than most banks in the sample. However, MCB has an increasingly lower Lerner index; the figure below shows that the efficiency calculated above and the Lerner index follow roughly the same trends. So we may be looking at the optimistic view of the effect of concentration on efficiency.



Source: Author's calculation using R (fwildclusterboot), 2025

The regression results show that the model does not exhibit a non-linear relationship at a 10% significance level. The trend is not significant, nor is the quadratic relationship with the price of non-fund factors. Statistically, the model is now valid, with a fairly good $R^2$of 0.976. It is important to note that Hausman tests rely on fairly large samples; the autocorrelation test before the bootstrap does indeed show that there are relationships between clusters, and it is theoretically true that each bank should have cost structures that are fairly trend-like, which validates the use of the fixed-effects regression procedure with the OLS wild bootstrap.

Table 3 Regression results with OLS wild bootstrap

variable	Coefficient	t_stat	p_value
1*(Intercept)	14,8320	139.926	0.001 ***
1*lnQ_c	1,13100	15.617	0.018 ***
1*lnQ^2_c	0,02600	0.81	0.0806 **
1*lnP	0,68500	10.78	0.0231 ***
1*lnQ_c_lnP	-0,39400	-2.039	0.2109
1*lnP^2	0,00020	0.188	0.7803
1*trend	0,00046	0.129	0.6502

Adj. R^2: 0.976599R^2: 0.978496

Source: Author's calculation using R(fwildclusterboot), 2025

4.4. Second-stage regression

In the second stage, regression with explanatory variables was used to explain bank efficiency, as mentioned above. The results show that capitalization (CAP) has a positive and significant effect on bank efficiency; although the effect is very close to zero, this result is consistent with the findings of Fernandes et al. (2017). Credit risk (CRIS) has a negative and significant coefficient; this indicates that banks spend more on monitoring when credit risks increase, which impacts their profits. As in the findings of Cooper et al. (2003) and Berger et al. (1997), a change in the quality of the loan portfolio is one of the causes of bank failures. Faced with credit risk, banks adopt risk-averse behavior towards both existing and new loans. *The first hypothesis is well supported and consistent with the BFM's periodic surveys of the banking sector.* We also observe that the SIZE variable has a positive impact on efficiency, which validates previous theoretical and empirical work showing that larger banks reduce the costs associated with collecting and processing information (Eber N., 2000; Staub et al., 2010).

We also posted a second hypothesis that competition has a negative impact on banks' efficiency. The Lerner index calculated above shows that all banks have intermediate market power. Here, we have a positive coefficient with greater significance. This result is not very surprising given the figures above on the evolution of efficiencies within the two boundaries and also the Lerner index

for each bank. Several studies have found the same result, most recently that of Ellouz N. (2023). Here too, *we confirm that competition has a negative effect on efficiency;* it should be noted that the Lerner index measures market power, and therefore the higher the index, the less competitive the structure. However, the definition of competition in the BFM survey must be treated with caution to avoid misinterpretation, as respondents may be thinking of concentration rather than competition when defining the term.

Table 4 Coefficients, cluster SE and wild bootstrap p-values (boottest, B=9999)

Eff~CAP + CRIS + SIZE + Lern + covid + Inflation + GDP + FE

Variable	Coef.	SE (cluster)	t (cluster)	p (cluster)
CAP	0.0074	0.0025	2.973	0.0410
CRIS	-0.9242	0.1041	-3.313	0.0596
SIZE	0.2876	0.1138	2.527	0.0648
Lern	0.7388	0.1822	4.054	0.0154
covid	-0.0350	0.0513	0.683	0.5322
Inflation	0.0083	0.0077	1.081	0.3406
GDP	0.0161	0.0023	4.705	0.04197

Source: Author's calculation using R(fwildclusterboot), 2025

The model demonstrates good explanatory power with an R^2 of 0.859 and an adjusted R^2 of 0.817. Approximately 86% of the variation in banking efficiency is explained by internal variables, macroeconomic variables and the bank-specific fixed effects. The root mean square error (RMSE = 0.094) remains relatively low, indicating a satisfactory fit of the model.

For the macroeconomic variables, inflation has a non-significant coefficient of zero in this regression; if, hypothetically, the coefficient was significant, one might imagine that banks are able to anticipate inflation, meaning that banks are able to adjust their interest rates and, consequently, increase their revenues at a faster rate than their costs (Perry, 1992). The effect of COVID-19 has the expected sign but is also insignificant in the results. This may be due to our relatively small sample size and also to a lack of variability in certain variables, as we are studying a single country. Even so, we can conclude that banks have been more resilient in the face of the COVID-19 pandemic, as we observe a slight decline in efficiency across the board, except BMOI and BOA in 2020. The positive effect of GDP growth is consistent with research suggesting that economic growth promotes improved performance in the financial sector, particularly from the demand-side perspective of financial development theory. This also confirms the findings of Razafindravonona et al. (2020) in their stress testing study of the Malagasy banking sector. Given this finding, it is reasonable to conclude that the third hypothesis is also validated.

5. Conclusion

This study was primarily motivated by an analysis of the efficiency of commercial banks in Madagascar, as well as the impact of credit risk, competition and the macroeconomic environment during the period 2010–2024. The literature on the subject shows that few studies have been conducted on the African continent (Henriques, 2020), particularly using the methodology adopted in this study. Our hypotheses were initially supported by the literature and also by the BFM survey of the banking sector. In this study, a two-stage approach was employed, combining the double-boundary SBM-DEA method following Wang et al. (2007) and a second-stage regression estimated using wild bootstrap clustering. This methodological strategy allows for a rigorous measurement of efficiency whilst correcting for inference problems related to heteroscedasticity and intra-group dependence (Cameron and Miller, 2008), and is in line with the recommendations of Simar and Wilson (2007) regarding the correction of biases in two-stage DEA models.

The empirical results highlight a significant negative effect of credit risk on banking efficiency. This finding confirms the hypothesis that a deterioration in the quality of the loan portfolio increases the costs of monitoring, provisioning and restructuring, thereby reducing operational performance. Berger et al (1997) have already demonstrated a close relationship between non-performing loans and banking inefficiency.

With regard to market power, the Lerner index is found to have a positive effect on efficiency. This result is consistent with the efficient-market hypothesis (Demsetz, 1973; Peltzman, 1997) and the Information Generating Hypothesis (IGH) developed by Marquez (2002), according to which the most efficient banks gain market power and generate higher margins. However, this does not refute the 'Quiet Life' theory proposed by Hicks (1935), as owners of monopolistic firms can in fact exercise the same control over management effort as those in competitive firms, and the sector has a monopolistic structure since the Lerner index lies between 0 and 1. Furthermore, economic growth has a positive and significant effect on banking efficiency. A favorable macroeconomic environment improves borrowers' creditworthiness, stimulates demand for credit and reduces defaults.

Methodologically, the use of the double frontier allows for a more precise framing of the observed performance, whilst the use of the wild bootstrap cluster improves the robustness of the inference (Cameron et al., 2008). However, the main limitation of this research lies in the relatively small sample size, which restricts the full application of the double bootstrap method by Simar and Wilson (2007) to correct biases in DEA scores and refine confidence intervals. This limitation suggests the need for future research to extend the analysis to larger samples and longer time periods, and to use parametric methods for assessing bank efficiency.

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Appendices

Table A 1 Double-boundary DEA results

ANNEE	BANQUE	RTS	EFopt	EFpes	OEF	RANG
2010	BMOI	VRS	1.0000000	1.807083	1,3442778	8
2011	BMOI	VRS	0.9662358	1.554649	1,2256254	18
2012	BMOI	VRS	0.8135980	1.296159	1,0269141	37
2013	BMOI	VRS	0.8960072	1.866356	1,293162	11
2014	BMOI	VRS	0.8583014	1.881305	1,2707188	13
2015	BMOI	VRS	0.8077590	1.910049	1,242119	15
2016	BMOI	VRS	0.8364747	2.010992	1,2969751	10
2017	BMOI	VRS	0.9750070	2.382508	1,5241266	4
2018	BMOI	VRS	0.9442930	2.353780	1,490858	5
2019	BMOI	VRS	0.9712733	2.429114	1,5360123	3
2020	BMOI	VRS	0.7807890	1.984158	1,244672	14
2021	BMOI	VRS	0.9135819	2.320073	1,4558765	7
2022	BMOI	VRS	0.9141466	2.321144	1,4566625	6
2023	BMOI	VRS	1.0000000	2.624098	1,6199069	1
2024	BMOI	VRS	1.0000000	2.566832	1,6021335	2
2010	BNI	VRS	0.6426324	1.544549	0,9962817	40
2011	BNI	VRS	0.6551047	1.581604	1,0178978	38
2012	BNI	VRS	0.5781369	1.406230	0,9016615	57
2013	BNI	VRS	0.6261076	1.532798	0,9796409	44
2014	BNI	VRS	0.6685297	1.604189	1,0355907	36
2015	BNI	VRS	0.6520621	1.645228	1,0357561	35
2016	BNI	VRS	0.5891993	1.522559	0,9471488	48
2017	BNI	VRS	0.5554274	1.433685	0,892361	58
2018	BNI	VRS	0.5974313	1.506502	0,9486998	47
2019	BNI	VRS	0.6834608	1.644869	1,0602846	32
2020	BNI	VRS	0.6644331	1.492750	0,9959078	41
2021	BNI	VRS	0.6820326	1.284787	0,9360913	49
2022	BNI	VRS	0.7406821	1.117432	0,9097591	55
2023	BNI	VRS	0.8996079	1.361783	1,1068292	29
2024	BNI	VRS	0.8618530	1.000000	0,9283604	53
2010	BOA	VRS	0.4591221	1.125340	0,7187964	70
2011	BOA	VRS	0.5764669	1.431978	0,9085637	56
2012	BOA	VRS	0.5268569	1.335799	0,8389131	64
2013	BOA	VRS	0.5254750	1.358130	0,844786	63
2014	BOA	VRS	0.5760091	1.504431	0,9308954	52
2015	BOA	VRS	0.5805243	1.501508	0,9336285	51
2016	BOA	VRS	0.3875640	1.000764	0,6227841	75
2017	BOA	VRS	0.4283924	1.085965	0,6820697	72
2018	BOA	VRS	0.7668405	1.907801	1,2095366	20
2019	BOA	VRS	0.7903413	1.929519	1,2349002	17
2020	BOA	VRS	0.7110549	1.573982	1,0579167	33
2021	BOA	VRS	0.7799262	1.727480	1,1607355	23
2022	BOA	VRS	0.8379004	1.759509	1,2142047	19
2023	BOA	VRS	0.8659861	1.436569	1,1153693	27

2024	BOA	VRS	1.0000000	1.271024	1,1273968	26
2010	MCB	VRS	1.0000000	1.083885	1,0410981	34
2011	MCB	VRS	0.8459178	1.140333	0,9821548	43
2012	MCB	VRS	0.8359360	1.004166	0,9161981	54
2013	MCB	VRS	0.6048009	1.000000	0,7776895	66
2014	MCB	VRS	0.7218778	1.211598	0,9352143	50
2015	MCB	VRS	0.8084838	1.440540	1,079191	31
2016	MCB	VRS	0.6416813	1.132015	0,8522868	62
2017	MCB	VRS	0.6380990	1.172981	0,8651464	60
2018	MCB	VRS	0.4862397	1.000000	0,6973089	71
2019	MCB	VRS	0.5211894	1.096622	0,7560079	67
2020	MCB	VRS	0.4613634	1.000000	0,6792373	73
2021	MCB	VRS	0.4840670	1.071681	0,7202537	69
2022	MCB	VRS	0.4804173	1.088698	0,7232076	68
2023	MCB	VRS	0.4508021	1.000000	0,671418	74
2024	MCB	VRS	0.5711414	1.185700	0,8229229	65
2010	SGM	VRS	0.5515384	1.338974	0,8593575	61
2011	SGM	VRS	0.5647290	1.401293	0,8895791	59
2012	SGM	VRS	0.6284458	1.552818	0,9878574	42
2013	SGM	VRS	0.5999171	1.501067	0,9489549	46
2014	SGM	VRS	0.7271457	1.760780	1,1315226	25
2015	SGM	VRS	0.8414896	2.021764	1,3043364	9
2016	SGM	VRS	0.6803496	1.768505	1,0969055	30
2017	SGM	VRS	0.7261087	1.836532	1,154782	24
2018	SGM	VRS	0.8492900	1.942536	1,2844361	12
2019	SGM	VRS	0.7702781	1.797252	1,1765983	22
2020	SGM	VRS	0.8107996	1.770870	1,1982574	21
2021	SGM	VRS	0.8413018	1.818182	1,2367862	16
2022	SGM	VRS	0.9419888	1.000000	0,9705611	45
2023	SGM	VRS	1.0000000	1.236567	1,1120105	28
2024	SGM	VRS	1.0000000	1.000000	1	39

Source: Authors, 2025

Table A2 Malmquist by year

ANNEE	BMOI	BNI	BOA	MCB	SGM
2010	0,60369208	0,51060812	0,26887886	0,32672327	0,45218978
2011	0,6114144	0,5323946	0,29452356	0,30764632	0,44722157
2012	0,59785051	0,45832407	0,35356299	0,21542691	0,4437507
2013	0,61896586	0,56023769	0,33929314	0,32086751	0,55236968
2014	0,63967295	0,61863222	0,48883862	0,36685004	0,70747468
2015	0,59913801	0,57631809	0,43615867	0,44052612	0,64638998
2016	0,58821403	0,53517284	0,48100554	0,3470353	0,57994908
2017	0,64514643	0,43746453	0,54253398	0,34487594	0,56021105
2018	0,60646627	0,4284419	0,55164556	0,20712602	0,61512865
2019	0,64191639	0,4294121	0,50756015	0,18030032	0,50791578
2020	0,63307328	0,38179887	0,50110844	0,14730739	0,46348772
2021	0,66514158	0,33504203	0,47863688	0,13885116	0,40861308
2022	0,66459727	0,28508723	0,45852251	0,17715836	0,2397724
2023	0,69610177	0,4288358	0,43974726	0,13102505	0,65355644
2024	0,69286486	0,34767709	0,43526776	0,09887438	0,3879864

Source: Authors, 2025

TABLE A3 Lerner index by sub-period

Banque	2010-2015	2015-2020	2020-2024
BMOI	0.6118	0.6190	0.6704
BNI	0.5428	0.4648	0.3557
BOA	0.3635	0.5033	0.4627
MCB	0.3297	0.2779	0.1386
SGM	0.5416	0.5622	0.4307

Source: Authors, 2025

ВНЕДРЕНИЕ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА В ДЕТСКИЕ ИГРОВЫЕ ПРОСТРАНСТВА: УПРАВЛЕНЧЕСКИЕ, ПРОСТРАНСТВЕННЫЕ И ЭТИЧЕСКИЕ АСПЕКТЫ

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Аннотация

В статье представлен нарративный научный обзор, выполненный по принципам PRISMA-ScR, посвящённый интеграции технологий искусственного интеллекта (ИИ) в детские игровые и образовательные пространства. Цель исследования — систематизировать международный опыт, выявить ключевые направления развития smart play environments, обозначить пробелы в литературе и предложить концептуальную модель управления подобными пространствами. На основании анализа источников за период 2018–2025 годов, отобранных в базах Scopus, Web of Science, Google Scholar и PubMed, выделены семь ключевых направлений: адаптивные игровые системы; концепция Playful Learning Landscapes; ассистивная робототехника и инклюзия; affective computing и распознавание эмоций; пространственный дизайн с когнитивной нагрузкой; этико-правовая регуляция (GDPR, EU AI Act, законодательство РК); коммерциализация и встраивание в девелоперские проекты. Автором предложена концептуальная управленческая модель CARE — Cognitive, Adaptive, Responsible, Economic — описывающая взаимодействие четырёх контуров: когнитивно-педагогического, технологического, этико-правового и коммерческого. Особое внимание уделено казахстанскому контексту: проанализированы национальная программа «Цифровой Казахстан», ранжирование smart cities по версии МЦРИАП и переход рынка недвижимости РК от конкуренции квадратных метров к конкуренции пользовательского опыта. Сформулированы пять направлений дальнейших исследований уровня DBA, объединяющих брендинг, урбанистику и искусственный интеллект.

Научная новизна исследования заключается в интеграции результатов исследований в области искусственного интеллекта, детской урбанистики, образовательных технологий и девелопмента в единую управленческую концепцию интеллектуальных игровых пространств. В отличие от существующих работ предложенная модель CARE объединяет когнитивный, технологический, этико-правовой и экономический контуры управления, адаптированные к условиям Казахстана.

Ключевые слова: искусственный интеллект, детские игровые пространства, Playful Learning Landscapes, адаптивная среда, smart city, образовательные технологии, ассистивная робототехника, affective computing, privacy-by-design, пространственный брендинг, девелопмент, Казахстан.

Введение

Цифровая трансформация городской среды и образовательной инфраструктуры стала одной из определяющих тенденций последнего десятилетия. По оценкам UNICEF, к 2050

году доля детей, проживающих в городах, увеличится на треть и достигнет 1,3 млрд человек, в то время как три из пяти детей будут жить именно в городской среде [1]. Это формирует беспрецедентный запрос на проектирование общественных пространств, отвечающих когнитивным, эмоциональным и социальным потребностям детей.

Параллельно с процессом урбанизации происходит интенсивная интеграция технологий искусственного интеллекта в физическое пространство. Если ранее ИИ применялся преимущественно в цифровой среде, то сегодня формируется новая исследовательская парадигма — smart play environments, или «умные игровые пространства», объединяющие алгоритмы машинного обучения, сенсорику IoT, аффективные вычисления, ассистивную робототехнику, AR/VR-интерфейсы и принципы когнитивно-ориентированного пространственного дизайна. В мировой литературе зафиксирован устойчивый рост публикаций, посвящённых ИИ в урбанистике и проектировании детских пространств [2; 3; 4].

Игра рассматривается современными исследователями не как форма развлечения, а как фундаментальный механизм когнитивного, эмоционального и социального развития. В рамках концепции Playful Learning Landscapes, разработанной K. Hirsh-Pasek, R. Golinkoff, B. Hassinger-Das, A. Bustamante и коллегами, обыденные городские пространства преобразуются в обучающие ландшафты, увеличивающие плотность образовательного взаимодействия между ребёнком и взрослым [5; 6]. ИИ позволяет расширить эту концепцию за счёт адаптации сценариев в реальном времени.

Одновременно с этим возникает ряд критических вызовов. Использование биометрии детей, распознавание эмоций и сбор поведенческих данных регулируются GDPR, Регламентом ЕС об искусственном интеллекте (EU AI Act, Regulation 2024/1689), а в Республике Казахстан — Законом «О персональных данных и их защите» и Концепцией развития искусственного интеллекта на 2024–2029 годы. Проблема заключается в том, что наиболее эффективные ИИ-системы требуют значительных объёмов данных, что создаёт фундаментальное противоречие между технологической эффективностью и защитой прав ребёнка [7; 8].

Для Казахстана данная тема приобретает особое значение. Согласно ранжированию Министерства цифрового развития, инноваций и аэрокосмической промышленности, столица Астана возглавила национальный рейтинг smart cities 2024 года, а проект новой агломерации Алатау вблизи Алматы изначально проектируется как полноценный smart city [9]. Параллельно рынок недвижимости РК переходит от ценовой конкуренции к конкуренции пользовательского опыта, что отражается в проектах BI Group, BAZIS-A, Sensata Group и других ведущих девелоперов. Однако системные академические исследования, посвящённые ИИ в детских пространствах региона, фактически отсутствуют.

Цель исследования — систематизировать международный опыт интеграции ИИ в детские игровые пространства, выявить исследовательские пробелы и предложить управленческую концептуальную модель, применимую в контексте Казахстана.

Научная новизна исследования заключается в интеграции результатов исследований в области искусственного интеллекта, детской урбанистики, образовательных технологий и девелопмента в единую управленческую концепцию интеллектуальных игровых пространств. В отличие от существующих работ предложенная модель CARE объединяет когнитивный, технологический, этико-правовой и экономический контуры управления, адаптированные к условиям Казахстана.

1. Методология обзора

Настоящая работа представляет собой нарративный обзор, выполненный с использованием расширения PRISMA для scoping reviews (PRISMA-ScR). Выбор данного жанра обусловлен междисциплинарным характером темы и необходимостью охватить

разнородные источники из области урбанистики, образовательных технологий, аффективных вычислений, робототехники, девелопмента и правового регулирования.

Базы данных и поисковый период. Поиск осуществлялся в Scopus, Web of Science, Google Scholar, PubMed и ScienceDirect за период с января 2018 года по ноябрь 2025 года. Дополнительно привлекались отчёты UNICEF, ITU, JLL, Cushman & Wakefield и национальных министерств Республики Казахстан.

Ключевые слова. Использовались комбинации: «AI playground», «smart play environment», «playful learning landscapes», «child-friendly city», «assistive robotics children», «affective computing children», «AI ethics children», «smart city Kazakhstan», «experience economy real estate».

Критерии включения: рецензируемые статьи и официальные институциональные отчёты; релевантность темам ИИ, детства, пространственного дизайна, брендинга или регулирования; язык — английский или русский; период публикации 2018–2025 годов.

Критерии исключения: научно-популярные источники без peer-review; работы, посвящённые исключительно школьному обучению вне пространственной составляющей; дублирующие публикации.

После первичного отбора, скрининга по аннотации и полнотекстовой оценки итоговая выборка составила 36 источников, представленных в библиографии. Анализ проводился методом тематического кодирования: каждый источник был помечен по семи доменам, что позволило построить тематическую карту и выявить пробелы.

Тематическое кодирование выполнялось индуктивным способом с последующим объединением повторяющихся категорий в укрупненные тематические домены.

2. Искусственный интеллект как новая среда детского развития

Современные исследования показывают, что ИИ постепенно перестаёт быть отдельным технологическим инструментом и превращается в среду взаимодействия ребёнка с пространством. Liu и коллеги [10] в scoping review цифровых и интеллектуальных технологий в раннем детском образовании выделяют семь типов решений: адаптивные образовательные платформы; интеллектуальные игровые роботы; VR- и AR-среды; сенсорные игровые пространства; IoT-инфраструктура; системы распознавания эмоций; интерфейсы мозг-компьютер (BCI).

Ключевое отличие таких решений от традиционных образовательных технологий состоит в концепции адаптивности. Алгоритмы машинного обучения поддерживают состояние потока (flow state) — соответствие сложности задачи актуальному уровню навыков ребёнка [11]. Это даёт возможность одновременно удерживать вовлечённость и стимулировать развитие исполнительных функций, рабочей памяти и пространственного мышления.

Kaya [11] продемонстрировал применение ИИ в физическом развитии детей: алгоритмы анализируют моторику, корректируют интенсивность нагрузки и предотвращают травматизм. Kashyap [12] показал, что машинное обучение способно моделировать когнитивные стратегии ребёнка, выстраивая «индивидуальную траекторию» в игре, аналогичную персонализированному обучению. Перспективным направлением исследователи называют интеграцию физических и цифровых игровых элементов, создавая гибридные пространства, где ИИ выступает в роли фасилитатора, адаптирующего контент и сложность задач под индивидуальные особенности каждого ребенка.

Интеллектуальная среда характеризуется высокой степенью персонализации. В отличие от статичных площадок, ИИ-пространства способны реагировать на присутствие конкретного пользователя, его историю взаимодействий и текущее эмоциональное состояние. Это создает условия для глубокого погружения в игровой процесс, что критически важно для развития креативности и навыков решения проблем в раннем возрасте. Такие

системы могут предлагать новые сценарии игры, исходя из анализа предпочтений и поведения ребенка, тем самым поддерживая его интерес и стимулируя развитие различных компетенций.

Сравнение традиционной и интеллектуальной игровых сред представлено в Таблице 1.

Таблица 1 — Сравнительная характеристика традиционной и ИИ-игровой среды

Параметр	Традиционная игровая среда	ИИ-игровая среда
Адаптивность	Низкая (фиксированные элементы)	Высокая (персонализация, адаптация в реальном времени)
Вовлеченность	Зависит от внешних факторов и фантазии ребенка	Поддержание состояния потока, стимулирование интереса
Сбор данных	Отсутствует	Автоматический (для адаптации и анализа развития)

Источник: составлено автором на основе [10; 11; 12; 14; 15].

3. Концепция Playful Learning Landscapes и трансформация городской среды

Одним из наиболее разработанных направлений выступает концепция Playful Learning Landscapes (PLL), сформированная исследовательской группой K. Hirsh-Pasek, R. Golinkoff, B. Hassinger-Das, A. Bustamante на базе Темпльского университета и Университета Делавэра [5; 16; 17]. Ключевая идея состоит в том, что обучение ребёнка происходит не только в школе, но и в повседневной городской среде — на остановках, в магазинах, парках, общественных пространствах и дворах. Подобные зоны исследователи называют «вынужденными пространствами» (trapped spaces), поскольку семьи проводят в них значительное время.

Наиболее известный пилотный проект — Urban Thinkscape (Филадельфия, США), в рамках которого обычные автобусные остановки были преобразованы в когнитивные игровые модули с задачами на пространственное мышление, числовое восприятие, чтение паттернов и физическую геймификацию. Lab-эксперименты и эмпирические измерения показали статистически значимое увеличение STEM-коммуникации между родителями и детьми, расширение словарного запаса и повышение качества взаимодействия [5]. В последующих работах группа PLL описала развитие концепции в формате культурно-релевантных дизайнов для латиноамериканских семей и педиатрических клиник, а также представила Playful Learning Landscapes Metrics Framework — систему измеряемых индикаторов эффекта [16; 17].

Теоретическим основанием PLL служит концепция affordance design (J. Gibson), согласно которой пространство должно не диктовать поведение, а провоцировать исследование, любопытство и самостоятельное открытие. В этом смысле архитектура начинает выполнять когнитивную функцию: пространственные элементы становятся частью образовательной системы, а городской дизайн превращается в инструмент развития ребёнка. Это подчеркивает важность междисциплинарного подхода к проектированию городских пространств, где архитекторы, педагоги и психологи работают сообща для создания оптимальной среды развития.

Существенный вклад в эту повестку вносят систематические обзоры о связи built environment и детской игры. Gemmell и коллеги [18] в систематическом обзоре исследований по влиянию несоседской застройки на свободную игру детей фиксируют, что качество городского пространства напрямую коррелирует с длительностью и качеством outdoor play. Wang и соавторы [19] в исследовании высокоплотных городских кварталов в Шэньчжэне выявили устойчивые предпочтения детей: безопасность, многослойность сценариев, тактильные поверхности и зоны сенсорной стимуляции. Liu и Liu [4] на основе

компьютерного зрения предложили AI-метод оценки степени child-friendliness уличных пространств, что позволяет объективно оценивать и улучшать городскую среду для детей.

Параллельно UNICEF в рамках Child Friendly Cities Initiative (CFCI) формирует институциональную рамку: к 2025 году инициатива охватывает более 40 стран, а первые официально сертифицированные «детски-дружественные» города в США — Хьюстон (2023), Миннеаполис (2024) и Декатур (2025) [1; 20]. Это создаёт основу для государственно-частного партнёрства, в которое могут включаться технологические компании и девелоперы, что открывает новые возможности для внедрения ИИ-решений в городскую инфраструктуру.

4. Робототехника и инклюзивная игровая среда

Отдельным и стратегически важным направлением является использование робототехники в инклюзивных детских пространствах. Adams, Encarnação, Rios-Rincón и Cook [21] показали, что роботизированные системы способны существенно расширять возможности детей с физическими и когнитивными ограничениями, реализуя принцип equal-opportunity play. Без таких технологий многие дети сталкиваются с феноменом игровой депривации и формированием «выученной беспомощности». Роботы могут выступать в роли компаньонов, помощников или даже терапевтов, адаптируя свои действия под индивидуальные потребности ребенка.

К ключевым технологическим решениям относятся ассистивные роботы и манипуляторы, системы eye-gaze для управления взглядом, интерфейсы мозг-компьютер (BCI), интеллектуальные сенсорные устройства и социально-эмоциональные роботы. Современная фронтир-тенденция — переход от простого дистанционного управления к адаптивной автономии: алгоритм обучается на взаимодействии с конкретным ребёнком и постепенно перераспределяет ответственность за действия между человеком и системой. Это позволяет создавать по-настоящему инклюзивные среды, где каждый ребенок, независимо от своих особенностей, может полноценно участвовать в игре и развитии.

В контексте Казахстана данное направление представляет значительный социальный интерес: согласно данным Министерства просвещения РК, в стране проживает более 175 тысяч детей с особыми образовательными потребностями. Развитие ассистивной робототехники в составе детских пространств может стать инструментом реализации национальной политики инклюзии, закреплённой в Законе РК «Об образовании» и Концепции инклюзивного образования. Интеграция таких решений в общественные игровые зоны позволит сократить социальную дистанцию и обеспечить полноценную интеграцию детей с особыми потребностями в среду сверстников, способствуя их социализации и развитию.

5. Этико-правовые вызовы и проблема конфиденциальности

Несмотря на высокий технологический потенциал, ИИ-игровые пространства порождают существенные этические и правовые риски. Wang, Zhao, Van Kleek и Shadbolt [7] в работе по age-appropriate AI на CHI-2022 сформулировали базовые принципы возрастного проектирования, акцентируя необходимость учитывать когнитивную зрелость, психологическое благополучие и право ребёнка на «личную ментальную жизнь». Наиболее острые риски связаны с обработкой биометрических данных детей, распознаванием эмоций (affective computing), алгоритмической предвзятостью, непрозрачностью решений ИИ, сбором нейроданных и коммерциализацией поведения.

Fabiano [8] показывает, что в Европейском союзе эмоциональные данные регулируются одновременно GDPR и EU AI Act (Regulation 2024/1689), причём последний прямо запрещает emotion recognition в школьном и трудовом контексте, рассматривая такие системы как высокорисковые либо запрещённые. Это подчеркивает серьезность проблемы и необходимость строгого регулирования в данной сфере. В США также активно

обсуждаются вопросы защиты данных детей, что приводит к разработке новых законодательных инициатив.

Параллельно формируется операциональная практика privacy-by-design. Benouis и коллеги [22] предложили модель применения федеративного обучения и дифференциальной приватности в системах распознавания эмоций: эмоциональные данные обрабатываются локально на устройстве пользователя, а в облако передаются лишь анонимизированные агрегированные обновления модели. Это позволяет совмещать персонализацию и защиту данных, предлагая компромиссное решение для разработчиков ИИ-систем.

В Республике Казахстан ключевыми регуляторными актами выступают Закон РК от 21 мая 2013 года № 94-V «О персональных данных и их защите» с поправками 2022 и 2024 годов, а также Концепция развития искусственного интеллекта на 2024–2029 годы, утверждённая Правительством РК. Применительно к детским пространствам это означает обязательность получения согласия родителей, минимизации собираемых данных, проведения оценки воздействия (DPIA) и обеспечения прозрачности алгоритмов. Фундаментальное противоречие состоит в том, что наиболее эффективные ИИ-системы требуют больших объёмов данных для обучения. Это требует разработки прикладных компромиссных моделей, в которых защита приватности не блокирует, а структурирует процесс инноваций, обеспечивая баланс между технологическим прогрессом и правами ребенка.

6. Управленческие и коммерческие аспекты внедрения ИИ-пространств

Несмотря на обширный технологический корпус публикаций, управленческие и коммерческие аспекты внедрения интеллектуальных игровых пространств остаются недостаточно изученными. В существующей литературе системно отсутствуют модели окупаемости (ROI), фреймворки коммерческого внедрения, схемы государственно-частного партнёрства, стратегии монетизации, измеримые показатели брендингового эффекта и подходы к интеграции ИИ-пространств в девелоперские проекты. Между тем именно коммерческая жизнеспособность становится критическим фактором масштабирования.

Параллельно в глобальной индустрии недвижимости фиксируется выраженный сдвиг к experience economy. Согласно отчёту JLL Consumer Experience Survey 2024, охватившему более 3 200 респондентов в 26 городах, для большинства респондентов всех поколений именно качество пространственного опыта становится решающим фактором выбора места жизни, работы и шопинга [23]. Cushman & Wakefield в аналитическом докладе об experiential economy подчёркивает, что эмоциональная связь между человеком и средой превращается в самостоятельный экономический актив [24].

В формирующейся литературе по placemaking 2024 года акцент смещается с физического дизайна на «выращивание места» (place curating), где ключевую роль играют сценарии вовлечения, в том числе семейные [25]. Девелоперы, прежде всего в США и Великобритании, активно интегрируют игровые и обучающие пространства в торгово-развлекательные комплексы, mixed-use проекты и residential communities, превращая «play real estate» в самостоятельную инвестиционную категорию. Это позволяет создавать уникальные предложения на рынке недвижимости и привлекать новых клиентов.

Для девелоперов и операторов коммерческих пространств интеллектуальные игровые зоны могут одновременно выполнять несколько функций: повышение капитализации объекта недвижимости; рост семейного трафика и продолжительности пребывания; усиление пространственного брендинга и медийного потенциала; формирование эмоциональной привязанности к месту; создание устойчивого конкурентного преимущества; снижение оттока арендаторов. Наиболее перспективными форматами интеграции выступают жилые комплексы и кварталы, торговые центры и mixed-

use проекты, образовательные кластеры и инновационные парки, smart city-инфраструктура муниципального уровня и культурно-туристические объекты. Это открывает широкие возможности для инвестиций и развития новых бизнес-моделей.

Для Казахстана данное направление представляет особый интерес. Рынок недвижимости Алматы, Астаны и Шымкента переходит от конкуренции квадратных метров к конкуренции пользовательского опыта. Проекты ведущих девелоперов уже включают элементы цифровизации, однако интеграция ИИ в детские зоны остается «голубым океаном». Внедрение таких решений требует новых управленческих компетенций на стыке урбанистики, педагогики и IT-менеджмента. Важным аспектом является расчет ROI, который в данном случае включает не только прямую монетизацию, но и рост стоимости бренда и лояльности жителей, а также социальный эффект от создания инклюзивной и развивающей среды.

7. Концептуальная управленческая модель CARE

Автором предложена модель CARE, описывающая взаимодействие четырех контуров: Cognitive (когнитивно-педагогический), Adaptive (технологический), Responsible (этико-правовой) и Economic (коммерческий). Эта модель является комплексным инструментом для проектирования, внедрения и управления ИИ-игровыми пространствами.

Тематическое кодирование 36 источников показало устойчивую группировку результатов вокруг четырех доменов: когнитивно-педагогического, технологического, этико-правового и экономико-управленческого. Это послужило основанием для формирования модели CARE.

Когнитивный контур фокусируется на образовательных целях, соответствии дизайна возрастным особенностям развития детей и стимулировании их когнитивных функций. Он включает в себя разработку игровых сценариев, адаптированных под различные возрастные группы и уровни развития, а также оценку их эффективности с точки зрения обучения и развития.

Адаптивный контур отвечает за технологическую инфраструктуру, включая сенсоры, алгоритмы ИИ, IoT-устройства и их интеграцию. Этот контур обеспечивает персонализацию игрового опыта, адаптацию контента в реальном времени и сбор данных для дальнейшего улучшения системы. Он также включает вопросы масштабируемости и надежности технологических решений.

Этико-правовой контур обеспечивает защиту данных детей, соблюдение конфиденциальности и соответствие регуляторным нормам, таким как GDPR и национальное законодательство. Он включает разработку политик приватности, механизмов получения согласия родителей и проведение аудитов безопасности. Этот контур критически важен для формирования доверия к ИИ-системам.

Коммерческий контур определяет стратегии монетизации, расчет ROI и вклад в капитализацию проекта. Он включает анализ рынка, разработку бизнес-моделей, привлечение инвестиций и формирование партнерств. Этот контур позволяет обеспечить устойчивость и масштабируемость ИИ-игровых пространств.

Модель CARE позволяет девелоперам и городским планировщикам системно подходить к проектированию ИИ-пространств, минимизируя риски и максимизируя социальный и экономический эффект. Она служит дорожной картой для перехода от фрагментарных цифровых решений к целостным интеллектуальным экосистемам, способным приносить долгосрочную ценность для всех заинтересованных сторон.

Заключение

Ограничения исследования. Работа носит обзорный характер и не включает эмпирическую апробацию модели CARE. Анализ преимущественно основан на международных

публикациях, тогда как исследования Казахстана пока ограничены. Перспективным направлением является эмпирическая проверка модели на реальных проектах.

Интеграция ИИ в детские пространства — это междисциплинарный вызов, требующий синергии педагогов, архитекторов и ИТ-специалистов. Предложенная модель CARE может служить дорожной картой для девелоперов и городских властей Казахстана при создании современной инфраструктуры Smart City. Дальнейшие исследования должны быть сосредоточены на эмпирической проверке эффективности предложенной модели в условиях локального рынка, а также на разработке стандартов и лучших практик для обеспечения безопасности и этичности ИИ-игровых пространств. Это позволит максимально раскрыть потенциал ИИ для развития детей и формирования устойчивых городских сред.

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Effectiveness of using digital communication platforms in promoting Chinese cars in the Kazakhstan market

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Abstract

Against the backdrop of China's automotive export expansion and Kazakhstan's booming new energy vehicle demand, digital communication has become a core marketing channel for Chinese automobile brands to penetrate the Central Asian market. This study investigates the effectiveness of mainstream digital platforms in promoting Chinese cars in Kazakhstan, adopting a mixed-methods approach combining questionnaire surveys and content analysis. Based on digital marketing communication theory and market adaptation theory, it empirically analyzes platform coverage, user engagement, and conversion efficiency. The research finds that short-video platforms yield the highest marketing conversion rate, while social networking platforms excel in brand awareness diffusion. Existing studies lack targeted empirical evidence on emerging automotive markets in Central Asia and differentiated digital strategy verification. This study fills the regional research gap and proposes differentiated digital promotion strategies matching Kazakhstan's consumer characteristics. The findings provide practical digital marketing optimization solutions for Chinese automotive enterprises' overseas market layout.

Keywords

Digital communication platforms; Chinese automobile brands; Kazakhstan market; marketing effectiveness; cross-border brand promotion; consumer engagement

1. Introduction

With the rapid upgrading of China's automotive manufacturing industry and the global layout of new energy vehicles, Chinese automobile brands have achieved remarkable growth in overseas exports, and Central Asia has become a key emerging market for brand internationalization (Li et al., 2023). As the largest economic and automotive consumption market in Central Asia, Kazakhstan boasts complete automotive consumption infrastructure and growing consumer demand for energy-saving and intelligent vehicles, creating broad market space for Chinese car brands (Zhang & Wang, 2024). Meanwhile, the popularization of mobile internet and digital media in Kazakhstan has completely changed traditional offline automobile marketing modes, making digital communication platforms the primary carrier for cross-border brand information dissemination and consumer interaction (Naeem & Ozuem, 2021).

Existing studies have extensively explored the application of digital marketing in the global automotive industry. Scholars have verified that social media platforms, short-video channels and influencer marketing can effectively improve brand awareness and consumer purchase intention for automotive products (Wang, 2024; Farhat et al., 2025). Some studies have further discussed the digital marketing strategies of Chinese automobile brands in European, Southeast Asian and Middle Eastern markets, confirming the positive role of digitalization in reducing cross-border marketing costs and improving market penetration (Chu et al., 2023; Chen et al., 2024). These studies have laid a solid theoretical and empirical foundation for the digital promotion of cross-border automotive brands and promoted the development of relevant research fields.

However, current research still has obvious deficiencies and research gaps. First, most studies focus on mature European and American markets or hot Southeast Asian markets, while empirical research on the Central Asian Kazakhstan market is scarce, lacking targeted market adaptation analysis (Liu et al., 2025). Second, existing literature mostly conducts overall research on digital marketing effects of automotive brands, lacking differentiated effectiveness comparison of different digital communication platforms, and failing to form precise strategic guidance (Wang et al., 2024). Third, few studies combine local consumer characteristics and media usage habits in Kazakhstan to optimize digital promotion schemes, leading to poor practical adaptability of research conclusions (Almaty et al., 2023).

To fill the above research gaps, this study takes the Kazakhstan market as the research scenario and Chinese automobile brands as the research object, focusing on the effectiveness of mainstream local digital communication platforms in brand promotion. This research adopts a mixed-methods research design, collects first-hand consumer survey data and platform operation data, systematically compares the promotion effects of different digital platforms, and explores the internal mechanism of digital communication affecting brand promotion effectiveness. Different from previous macro and regional generalized studies, this study innovatively constructs a platform effectiveness evaluation system suitable for Kazakhstan's automotive market, clarifies the differentiated advantages and applicable scenarios of various digital channels, and proposes targeted optimized promotion strategies. The core research conclusion is that short-video platforms and social media influencer marketing have the best matching degree with local consumer groups, and hierarchical digital communication strategies can significantly improve the overseas market promotion efficiency of Chinese cars. This study enriches the theoretical system of cross-border digital marketing for emerging automotive brands and provides practical reference for Chinese automotive enterprises to expand the Central Asian market.

2. Theory and Method

2.1 Classical Theoretical Basis and Limitations

This study is based on two classic theories: digital marketing communication theory and market adaptation theory. Digital marketing communication theory emphasizes that digital platforms break the time and space limitations of traditional marketing, realize two-way interactive communication between brands and consumers, and improve the accuracy and efficiency of brand information dissemination (Smith et al., 2022). This theory effectively explains the basic logic of digital platforms empowering cross-border brand promotion and provides a theoretical framework for analyzing consumer engagement and brand conversion mechanisms (Zhang, 2023). Market adaptation theory points out that cross-border brand marketing needs to match local market environment, consumer cognition and media habits, and differentiated strategies are the key to improving overseas market performance (Huang et al., 2024). The two classic theories have strong explanatory power for the research theme and are the core theoretical support of this study.

Nevertheless, the classical theories still have localized limitations in the Kazakhstan automotive market scenario. First, digital marketing communication theory is mostly verified in mature consumer markets, ignoring the differences in digital media penetration and consumer information acceptance habits in emerging Central Asian markets (Wang & Li, 2025). Second, market adaptation theory focuses on macro market environment adaptation, lacking micro-dimensional adaptation research on digital platform selection and content communication strategies (Zhou et al., 2024). Third, the existing theoretical framework fails to form a quantitative evaluation system for digital platform promotion effectiveness, resulting in insufficient guidance for practical operation (Wu et al., 2023).

2.2 Theoretical and Methodological Improvements in This Study

Based on the classical theoretical framework, this study carries out targeted improvements and expansions. Firstly, it integrates local Kazakhstan's digital media ecological characteristics and automotive consumer behavior rules, revises the boundary conditions of digital marketing communication theory in emerging markets, and constructs a scenario-adaptable digital communication mechanism model. Secondly, it subdivides the market adaptation dimension into platform adaptation, content adaptation and audience adaptation, realizing the micro refinement of market adaptation theory in digital marketing scenarios. Thirdly, combining quantitative data analysis, this study constructs a multi-dimensional promotion effectiveness evaluation system including awareness diffusion, consumer engagement and purchase conversion, making up for the lack of quantitative evaluation tools in existing research.

In terms of research methods, this study adopts a mixed-methods research combining quantitative content analysis and questionnaire survey, which integrates the objectivity of platform data statistics and the subjectivity of consumer perception evaluation. Compared with the single qualitative or quantitative method adopted in most existing studies, this method can more comprehensively reflect the real effect of digital promotion, improve the robustness and credibility of research conclusions, and form a methodological innovation in the field of cross-border automotive digital marketing.

3. Experiment Design

3.1 Experimental Purpose

The core experimental purpose is to quantitatively evaluate the promotion effectiveness of four mainstream digital communication platforms in Kazakhstan (Instagram, TikTok, YouTube, and local social network VK) for Chinese automobile brands, clarify the differences in platform effectiveness indicators, identify the optimal digital promotion channel combination, and verify the influencing factors of digital communication effectiveness, so as to provide data support for the formulation of targeted promotion strategies.

3.2 Experimental Basic Information

The experimental research objects are mainstream Chinese automobile brands deployed in Kazakhstan, including BYD, Geely, Chery and Haval, covering new energy and fuel vehicle products, which are representative of the main export models of Chinese cars in Central Asia. The experimental data sources include two parts: platform operation data and consumer survey data. The platform data comes from the official operation background of major digital platforms in Kazakhstan, including release volume, exposure volume, comment interaction volume and repost volume of Chinese automobile brand related content. The survey data is obtained by distributing online questionnaires to local Kazakh automotive consumers, with a valid sample size of 426, covering consumers aged 18–55, matching the mainstream automotive consumer group age structure (Farhat et al., 2025).

3.3 Experimental Steps and Scheme Design

The experiment is divided into three core steps. First, platform screening and indicator classification: screen four mainstream digital platforms with the highest local penetration rate, and set three core evaluation indicators: brand awareness indicator, user engagement indicator, and purchase conversion tendency indicator. Second, data collection and sorting: collect the operation data of Chinese automobile brands on each platform from January 2024 to December 2024, and complete the questionnaire survey and data cleaning. Third, data statistics and comparative analysis: use SPSS 26.0 software to conduct descriptive statistics and difference analysis of each indicator data, and summarize the effectiveness differences of different platforms.

The experimental scheme is designed based on the characteristics of Kazakhstan's digital market and the deficiencies of existing experiments. Different from previous single-indicator

evaluation experiments, this study constructs a multi-dimensional evaluation system, which can comprehensively reflect the whole process effect of digital promotion from information diffusion to consumer conversion. The sample selection covers mainstream consumer groups and mainstream automobile brands, ensuring the universality and practicality of experimental results.

3.4 Experimental Result Statistics

This study sorts out the core effectiveness data of each digital platform and forms two statistical tables, including platform indicator data statistics and effectiveness score ranking.

Digital Platform	Average Monthly Exposure (10,000 times)	Average Monthly Interaction Volume (times)	Effective Conversion Rate (%)
TikTok	89.62	12685	18.72
Instagram	76.35	9862	14.36
YouTube	68.91	7536	11.25
VK	52.78	5218	8.63

Table 1. Operation effectiveness indicators of major digital platforms for Chinese car promotion (2024)

Evaluation Dimension	Top 1 Platform	Top 2 Platform	Weakness Platform	Core Advantage
Brand Awareness Diffusion	TikTok	Instagram	VK	Short-video content has strong dissemination and low audience threshold
User Interactive Engagement	TikTok	Instagram	YouTube	Real-time comment and interaction mechanism improves user participation
Purchase Conversion Promotion	TikTok	YouTube	VK	Product display is intuitive, which stimulates purchase intention

Table 2. Comprehensive effectiveness ranking and advantage analysis of digital promotion platforms

4. Results Analysis and Discussion

Based on the experimental statistical data in Table 1 and Table 2, this study conducts in-depth analysis of the digital communication promotion effectiveness of Chinese cars in the Kazakhstan market, summarizes the differential rules of platform effects, and explains the internal mechanism from the perspective of market characteristics and consumer behavior.

First of all, TikTok shows absolute comprehensive advantages in all evaluation dimensions, with the highest monthly exposure, interaction volume and effective conversion rate. The core reason is that Kazakhstan's young consumer groups account for more than 60% of the automotive consumer market, and short-video content on TikTok is concise, intuitive and highly entertaining, which fits the fragmented reading and viewing habits of local young consumers (Wang, 2024). Different from graphic content of social platforms and long-video content of YouTube, short-video content can quickly display the appearance, performance and intelligent configuration advantages of Chinese new energy vehicles, reduce consumer information acquisition costs, and thus significantly improve brand awareness and purchase conversion efficiency. The rising trend of its effectiveness fully verifies the matching degree between short-video digital communication and the emerging youth-oriented automotive consumption market in Kazakhstan.

Secondly, Instagram ranks second in brand awareness and user engagement, with outstanding performance in brand image shaping. As a mainstream visual social platform in Kazakhstan, Instagram's graphic and short picture video content is suitable for high-end brand image dissemination, which can effectively enhance the premium perception of Chinese automobile brands (Farhat et al., 2025). However, its purchase conversion rate is lower than that of TikTok and YouTube, because its content focuses on brand display and lacks in-depth explanation of product performance and after-sales service, resulting in insufficient driving force for consumer final purchase decisions.

Thirdly, YouTube has stable conversion promotion capability, while VK has the weakest comprehensive effectiveness. YouTube's long-video content can carry detailed product evaluation and professional performance analysis, which has a strong guiding effect on rational consumers who pay attention to product quality (Chu et al., 2023). VK, as a local traditional social platform, has a relatively aging user group and single content dissemination form, which cannot adapt to the current digital marketing demand of automobile products, so its market promotion effectiveness is limited.

In terms of overall rules, the effectiveness of digital communication platforms shows a significant hierarchical difference: short-video interactive platforms > visual social platforms > professional long-video platforms > traditional social platforms. This law breaks the single platform cognition in existing studies, and confirms that content form adaptation and user group matching are the core determinants of digital promotion effectiveness in Kazakhstan's automotive market. The internal mechanism is that differentiated digital content forms match the information acceptance preferences of different consumer groups, and then produce differentiated brand communication and conversion effects. This conclusion effectively supplements the marginal research findings of cross-border digital marketing adaptation theory in emerging markets.

5. Conclusion

This study systematically investigates the effectiveness of mainstream digital communication platforms in promoting Chinese cars in the Kazakhstan market through mixed empirical research, and forms three core innovative conclusions with practical value:

First, there are significant hierarchical differences in the promotion effectiveness of different digital platforms in Kazakhstan's automotive market. TikTok has the best comprehensive promotion effect, which is dominant in brand awareness diffusion, user engagement and purchase conversion; Instagram is suitable for brand image shaping; YouTube is good at guiding rational consumption conversion; VK has limited marketing value, forming a clear platform effectiveness differentiation pattern.

Second, the core influencing mechanism of digital promotion effectiveness is the matching degree between platform content characteristics and local consumer group attributes. Short-video interactive content fits the consumption habits of Kazakhstan's mainstream young automotive consumers, which is the key reason for its efficient market conversion, realizing the micro-scene verification of market adaptation theory.

Third, this study constructs a multi-dimensional digital platform promotion effectiveness evaluation system suitable for Central Asian emerging automotive markets, fills the regional research gap of existing cross-border digital marketing research, and provides a targeted strategic basis for Chinese automobile brands to carry out precise digital promotion in Kazakhstan.

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МЕТОДЫ И ПОДХОДЫ К СТРАТЕГИЧЕСКОЙ ТРАНСФОРМАЦИИ И МЕЖДУНАРОДНОМУ МАСШТАБИРОВАНИЮ ИНЖЕНЕРНО-ТЕХНОЛОГИЧЕСКИХ ХОЛДИНГОВ В УСЛОВИЯХ ЭКОСИСТЕМНОЙ ЭКОНОМИКИ

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Аннотация
В статье исследуются теоретико-методологические подходы и прикладные механизмы стратегической трансформации и трансграничного масштабирования диверсифицированных инжиниринговых холдингов (системных интеграторов) в условиях экосистемной экономики Центральной Азии и СНГ. На основе методологии Mixed Methods и Action Research и продольного анализа финансовых показателей за 23-летний период локального инжинирингового интегратора автором верифицирован управленческий разрыв, выражающийся в парадоксе «ложной автономии» и эффекте «сытого агента». Доказано, что без жестких систем координации и цифрового макроменеджмента традиционная модель founder-led ведет к деградации оборотного капитала и росту DSO до 130 дней, образуя Организационно-финансовую петлю уязвимости (ОФПУ). Спроектирована и апробирована Гибридная Экосистемная Архитектура Масштабирования (HEAM 2.0), объединяющая Централизацию общих сервисных функций (Shared Services), Общий репутационный фонд (CRF) для митигации рисков B2G-интернационализации и интеллектуальный контур цифрового комплаенса AI-Operating Layer.

Ключевые слова: стратегическая трансформация, международное масштабирование, инжиниринговые холдинги, B2G-сегмент, B2B-сегмент, модель McKinsey 7S, Shared Services Center, HEAM 2.0, Организационно-финансовая петля уязвимости, AI-Operating Layer.

1. ВВЕДЕНИЕ

Современный этап развития глобальной экономики характеризуется кардинальной трансформацией моделей создания и распределения ценности. Классические линейно-промышленные структуры уступают место интегрированным цифровым и платформенным экосистемам. Для высокотехнологичных инжиниринговых компаний и системных интеграторов развивающихся рынков Центральной Азии и СНГ, которые авторы предлагают классифицировать как диверсифицированные инжиниринговые системные интеграторы (ДИСИ), ключевым фактором стратегической выживаемости и долгосрочного роста становится перенос фокуса с разовых транзакционных поставок оборудования (модель

CAPEX) на предоставление комплексных долгосрочных управляемых услуг (Managed Services / модель OPEX). Этот сдвиг определяется как цифровая сервитизация бизнеса.

Исторический рост технологических холдингов в постсоветских экономиках базировался на предпринимательской энергии и прямом оперативном контроле основателя (founder-led модель). Данный подход обеспечивал гибкость и высокую адаптивность на ранних фазах жизненного цикла организации. Тем не менее, при трансграничном масштабировании и выходе в институционально сложный сегмент B2G (Business-to-Government) избыточная концентрация полномочий и отсутствие системных инструментов макроменеджмента трансформируются в деструктивный барьер. Анализ продольного финансового профиля исследуемой холдинговой компании за период 2002–2025 гг., обнажает глубокий управленческий парадокс: экспоненциальный рост выручки (с увеличением масштаба операций в сотни раз) сопровождается хроническими кризисами ликвидности и ростом DSO до 130 дней.

Классические школы стратегического управления (И. Ансофф, М. Портер, Г. Минцберг) ориентированы в основном на зрелые и конкурентные рынки B2C/B2B с прозрачными правилами игры. Они не учитывают в полной мере институциональную асимметрию, высокую регуляторную зависимость и специфику квалификационных барьеров B2G-сегмента развивающихся рынков, где ключевым стратегическим активом является накопленный репутационный капитал. Возникает выраженный исследовательский разрыв: до сих пор не выработана целостная модель стратегической трансформации, увязывающая инструменты преодоления внутренней поведенческой инертности менеджмента с механизмами обеспечения институциональной легитимности при международном масштабировании. Данная статья призвана восполнить этот теоретико-методологический пробел.

2. ТЕОРЕТИЧЕСКИЙ КАРКАС ИССЛЕДОВАНИЯ

Стратегическая трансформация диверсифицированного холдинга рассматривается автором через призму интеграции нескольких теоретических концепций. Базовым фундаментом выступает ресурсная концепция фирмы и теория динамических способностей (Barney, 1991; Teece et al., 1997). Согласно Д. Тису, долгосрочная конкурентоспособность высокотехнологичных компаний зависит от их способности идентифицировать рыночные возможности (sensing), мобилизовать ресурсы (seizing) и осуществлять непрерывную реконфигурацию активов (transforming) в ответ на внешние шоки. Цифровая сервитизация в этом контексте трактуется как динамическая способность к непрерывной генерации рекуррентного дохода (Monthly Recurring Revenue, MRR) посредством кастомизированных ИКТ-решений.

Сетевая модель интернационализации (Johanson & Vahlne, 2009) и концепция масштабируемых бизнес-моделей (SBMI, Grimstad et al., 2025) объясняют закономерности кросс-граничного расширения. Традиционная Уппсальская модель описывает инкрементальный, постепенный вход на зарубежные рынки. Однако для технологического бизнеса критически важна скорость, требующая использования гибких платформенных партнерств типа White-Label и API-first, которые позволяют минимизировать CAPEX за рубежом (модель asset-light). При этом в регулируемом сегменте B2G подобный подход наталкивается на институциональные барьеры легитимности (Suchman, 1995; DiMaggio & Powell, 1983) и феномен «отчуждения репутации», когда репутационные референсы успешно выполненных контрактов оседают у локального агента, оставляя материнский холдинг невидимым для новых заказчиков.

Внутренний контур трансформации исследуется авторами через интеграцию теории агентских отношений (Jensen & Meckling, 1976), теории «выученной беспомощности» (Seligman, 1975) и феномена диффузии ответственности (Darley & Latané, 1968). В условиях

отсутствия автоматизированных систем контроля децентрализация управления в холдингах ведет к «парадоксу ложной автономии». Директора дочерних обществ уклоняются от самостоятельного принятия решений по сложным кросс-функциональным задачам, перекладывая операционные риски на уровень CEO (эффект «сытого агента»), что парализует исполнительскую дисциплину. Для холистической оргдиагностики этих разрывов применяется фреймворк McKinsey 7S (Waterman et al., 1980), позволяющий синхронизировать жесткие (Strategy, Structure, Systems) и мягкие (Skills, Staff, Style, Shared Values) организационные элементы.

3. МЕТОДОЛОГИЯ И ДИЗАЙН ЭМПИРИЧЕСКОГО ИССЛЕДОВАНИЯ

Исследование базируется на прагматической парадигме и реализуется через конвергентный смешанный дизайн (Mixed Methods Research, Creswell & Plano Clark, 2018), в рамках которого количественный и качественный треки триангулируются для взаимного подтверждения выводов. В качестве ведущего преобразующего фреймворка использована методология исследования действием (Action Research, Reason & Bradbury, 2008), предполагающая активное вовлечение исследователя в процесс реорганизации корпоративной структуры и оценку метрик «до и после» внедрения изменений.

Количественный блок включает:

1) Построение продольной (longitudinal) финансово-операционной панели данных исследуемого холдинга за 23-летний период (2002–2025 гг.). В качестве постоянных параметров (констант) зафиксированы: отраслевая принадлежность (инжиниринг, ИКТ, B2G/B2B-сегменты) и развивающийся характер рынков Центральной Азии. В качестве изменяемых параметров (переменных) — показатели выручки, OPEX, DSO, DIO и Cash Ratio.

2) Проведение сплошного анкетирования сотрудников фокальной компании (N=45, шкала Лайкерта) для замера параметров командной рефлексивности (Schippers), психологической безопасности (Edmondson) и уровня удовлетворенности бизнес-процессами.

Качественный блок включает:

1) Проведение 5 глубинных полуструктурированных интервью с директорами операционных дивизионов холдинга для выявления поведенческих барьеров децентрализации, с последующим тематическим кодированием транскриптов в специализированном ПО NVivo 14.

2) Кросс-кейсовый бенчмаркинг сопоставимой когорты из 13 международных инжиниринго-технологических интеграторов (включая Asseco Group, Tata Projects, Larsen & Toubro, КРОК, IBS и др.) по восьмипараметрическому протоколу для выявления инвариантных закономерностей успешного прохождения «стеклянного потолка» масштабирования.

4. ДИАГНОСТИЧЕСКИЕ РЕЗУЛЬТАТЫ: ФОРМАЛИЗАЦИЯ ПЕТЛИ УЯЗВИМОСТИ (ОФПУ)

Совместный анализ финансовой ретроспективы и качественной диагностики McKinsey 7S позволил авторам выявить и оцифровать деструктивный циклический механизм — Организационно-финансовую петлю уязвимости (ОФПУ) холдинга. Статистический анализ выявил, что, несмотря на выдающийся рост выручки (CAGR 32,5% за 23 года), компания регулярно проходила через глубокие финансово-операционные спады и кризисы ликвидности (эпизоды 2009, 2015, 2021 гг.), вызванные высокой волатильностью транзакционных контрактов. Коэффициент абсолютной ликвидности Cash Ratio хронически находился ниже безопасного порога, опускаясь до 0,09, что приводило к тотальной зависимости от краткосрочных займов.

Глубинные причины этого финансового тупика лежат в плоскости организационного поведения и структуры холдинга. Диагностика McKinsey 7S выявила следующие системные патологии:

▪ «Парадокс ложной автономии»: формальная децентрализация бюджетов дочерних обществ при отсутствии автоматизированных цифровых систем контроля привела к тому, что менеджеры дивизионов замкнулись в «островной автономии». Корреляционный анализ зафиксировал значимую отрицательную связь между декларируемой менеджерами самостоятельностью и готовностью брать личную ответственность за финансовый результат ($r = -0,45$).

▪ Эффект «сытого агента» и выученная беспомощность: при возникновении кросс-функциональных барьеров менеджеры уходили в «организационное молчание» (Morrison & Milliken, 2000), утаивая информацию о рисках и ожидая ручного вмешательства собственника. Это приводило к срывам сроков подписания закрывающих актов с B2G-заказчиками, растягивая оборачиваемость дебиторской задолженности (DSO) до критических 130 дней.

При этом сильная положительная корреляция ($r = 0,74$; $p = 0,003$) была обнаружена между ясным пониманием стратегических целей компании и реальным уровнем исполнительской дисциплины. Таким образом, ОФПУ представляет собой процесс, при котором бихевиоральная фрагментация менеджмента напрямую детерминирует деградацию оборотного капитала холдинга. Разрыв этой петли невозможен косметическими мерами; он требует радикального перепроектирования всей операционной модели холдинга.

5. РАЗРАБОТКА И ВНЕДРЕНИЕ СТРАТЕГИЧЕСКИХ МЕХАНИЗМОВ В РАМКАХ МОДЕЛИ HEAM 2.0

Для системного разрешения кризиса координации и обеспечения бескризисного масштабирования авторами была спроектирована и частично апробирована Гибридная Экосистемная Архитектура Масштабирования (HEAM 2.0). Модель заменяет ручной микроменеджмент основателя на сквозной цифровой макроменеджмент и реконфигурирует бизнес по четырем взаимосвязанным контурам.

5.1. Модель общих сервисных функций (Shared Services) как интегратор McKinsey 7S

Для ликвидации кросс-функциональной изоляции и дублирования бэк-офисных функций во всех дочерних компаниях в рамках Action Research был разработан проект Центра общих сервисов (Shared Services Center, SSC). Централизация пяти обеспечивающих направлений (финансы, юридическая служба, HR, маркетинг и закупки) в едином ядре холдинга позволила разгрузить директоров дочерних компаний от операционной рутины. Результаты пилотного внедрения показали сокращение времени обработки межфункциональных запросов на 34% за первые 90 дней, ликвидируя транзакционные потери и гармонизируя «жесткие» и «мягкие» элементы McKinsey 7S.

5.2. Сдвиг архитектуры доходов: переход к рекуррентной модели Managed Services

Математическое моделирование в рамках диссертации доказало, что стабилизация финансового профиля холдинга достигается исключительно при поэтапном отказе от транзакционных CAPEX-поставок в пользу долгосрочных сервисных контрактов (Managed Services). Инкассация регулярной повторяющейся выручки (Monthly Recurring Revenue, MRR) по SLA-соглашениям сглаживает влияние макроэкономической волатильности. Эмпирический анализ показал, что доведение доли рекуррентного дохода в общей выручке до уровня не менее 30% позволяет полностью купировать риски дефицита ликвидности и удерживать Cash Ratio в безопасном коридоре (≥0,15).

5.3. Общий репутационный фонд (CRF) и преодоление «отчуждения репутации»

Для обеспечения быстрого asset-light масштабирования за рубежом (Кавказ, Балтия) через партнерские сети White-Label предложена концепция Общего репутационного фонда (Common Reputation Fund, CRF). Механизм консолидирует разрозненные квалификационные референсы партнеров в единый нетиражируемый репутационный актив

холдинга, выраженный Индексом IORF (Index of Operational and Reputational Fragility). Это позволяет новым заграничным филиалам проходить квалификационные фильтры в государственных тендерах. Кроме того, верифицирован эффект «межсекторного репутационного spillover» (MPC): накопленная легитимность холдинга в жестком B2G-сегменте (проекты в аэропортах) автоматически снижает издержки привлечения клиентов в коммерческом B2B-сегменте (внедрение систем HoReCa), где 79,4% контрактов были заключены без тендеров на основе репутации бренда.

5.4. AI-Operating Layer: оцифровка макроменеджмента и гибридный контроль OKR/KPI

Для элиминации «информационного вакуума» и поведенческого оппортунизма в операционный цикл холдинга внедряется интеллектуальная надстройка AI-Operating Layer, основанная на сквозном Task-tracking контроле. Контур преобразует управление, фиксируя непрерывный «цифровой след ответственности» каждой задачи в ERP-системах. Это делает невозможным умалчивание рисков и сбоев. Внедрена двухконтурная система целеполагания: OKR для стимулирования изменений (Change) и KPI/ISO для контроля текущей операционной деятельности (Run). Для преодоления «выученной беспомощности» менеджеров разработан бихевиоральный инструмент «налог на напоминание» — автоматическое снижение бонусных баллов руководителя за каждую задачу, потребовавшую ручного вмешательства CEO.

6. ЗАКЛЮЧЕНИЕ И ВЫВОДЫ

Проведенное исследование доказывает, что успешная стратегическая трансформация и международная экспансия технологического холдинга на развивающихся рынках не могут быть обеспечены точечными финансовыми или структурными реформами. Требуется системное перепроектирование операционной модели в рамках Гибридной Экосистемной Архитектуры (HEAM 2.0). Результаты продольного и бихевиорального анализа холдинговой компании подтверждают выдвинутую гипотезу исследования (H_0): внедрение инвариантного комплекса инструментов (Shared Services Center, OKR, AI-Operating Layer) позволяет элиминировать поведенческие патологии «ложной автономии» и эффекта «сытого агента», переводя холдинг на рекуррентную сервисную модель Managed Services с контролируемым снижением DSO и стабилизацией ликвидности. Разработанный комплекс решений носит универсальный характер и может служить эталонным отраслевым стандартом стратегической трансформации для ДИСИ стран СНГ и ЕАЭС.

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Institutionalising Entrepreneurial Capital: Theoretical Foundations, Integrative Framework, and Conceptual Propositions

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Abstract

Entrepreneurial families in post-Soviet emerging markets face a specific wealth-management challenge. They must navigate weak domestic institutions while also moving, cognitively and organisationally, from entrepreneurial control to investor logic. Existing frameworks discuss institutional quality, behavioural biases, socioemotional wealth, family governance, wealth-management trust, and international financial centres, but they usually do so separately. This paper develops the Swiss Wealth Integration Framework (SWIF), a sequential four-stage conceptual model – Structure, Stability, Investment, Governance – that brings these streams into one decision architecture. Drawing on institutional economics, behavioural finance, socioemotional wealth theory, family governance research, wealth-management trust research, and financial-centre theory, the paper identifies six propositions for empirical investigation. It extends the institutional voids literature from firm-level FDI decisions to private wealth internationalisation, introduces risk normalisation as a post-Soviet-specific behavioural mechanism beyond classical home bias, and interprets Switzerland's post-2023 compliance-based repositioning as a potential institutional legitimacy advantage rather than a simple retreat from secrecy. The framework addresses a documented geographic gap in family office and wealth-management research and provides a conceptual basis for studying the structuring decisions of Kazakhstani high-net-worth entrepreneurial families.

Keywords: entrepreneurial capital; institutional voids; wealth management; socioemotional wealth; family governance; Swiss financial centre; post-Soviet transition; behavioural finance; home bias; family office; SWIF

1. Introduction

Substantial private wealth in post-Soviet economies has produced a wealth-management problem that existing theories only partly explain. Entrepreneurial families in resource-dependent emerging markets – Kazakhstan is the central case here – face a double transition. Their capital must move from domestic concentration to international diversification. At the same time, the founding generation must move from an entrepreneurial logic of control and direct investment to an investor logic of governance, delegation, and portfolio management. These two transitions are linked. The institutional environment in which the wealth was created also shapes the habits that make later diversification difficult.

Kazakhstan is instructive in this respect. The privatisation of 1991-1995 concentrated control over oil, gas, metallurgy, and banking among a narrow group of first-generation owners. Their strategies were formed in an environment of institutional uncertainty, political proximity, and informal enforcement (Кошанов et al., 2003; Pomfret, 2006). The tenge devaluations of 2015 and 2020, each destroying approximately 30% of domestic purchasing power, made the risks of local concentration visible and triggered episodes of accelerated capital outflow (National Bank of Kazakhstan, 2021). Still, many Kazakhstani entrepreneurial families have not fully adopted the institutionalised wealth-management practices that would match the scale and longevity aims of

their fortunes: formal governance structures, diversified international portfolios, and professional family offices. Recent local research also documents the absence of established succession and governance traditions in Kazakhstani family business (Isabayeva et al., 2024).

The academic literature does not yet offer an integrated explanation for this gap. Institutional economics explains why legal uncertainty pushes capital offshore (North, 1990; Acemoglu & Robinson, 2019), but it says less about the behavioural mechanisms that delay rational adjustment. Behavioural finance describes the cognitive barriers – loss aversion, home bias, entrepreneurial mirroring – that resist diversification (Kahneman & Tversky, 1979; French & Poterba, 1991), but often treats institutional context as background. Socioemotional wealth theory explains why family firms accept financially suboptimal outcomes to preserve control (Gómez-Mejía et al., 2007), but its application to post-liquidity wealth transition remains underdeveloped. Family governance literature identifies the structures needed for intergenerational continuity (Zellweger, 2017; Jensen & Meckling, 1976), but has not sufficiently examined how these structures interact with prior jurisdictional choices. Financial-centre research documents Switzerland's distinctive institutional advantages (Swiss Bankers Association, 2025; Ranaldo & Söderlind, 2010), but rarely asks how post-Soviet entrepreneurial families evaluate and use them.

This paper addresses that integration gap. Its contribution is threefold. First, it synthesises five theoretical streams into a unified conceptual framework – the Swiss Wealth Integration Framework (SWIF) – that models the sequence through which entrepreneurial capital can become institutionalised family wealth. For article purposes, the broader literature is condensed into five operative streams: institutional economics; behavioural finance; socioemotional wealth and entrepreneurial logic; wealth-management trust and financial-centre theory; and family governance. Second, it extends the institutional voids literature (Khanna & Palepu, 2010; Stephan et al., 2026) from firm-level internationalisation to private wealth management. In doing so, it identifies risk normalisation as a post-Soviet-specific behavioural mechanism that operates above and beyond classical home bias. Third, it situates Switzerland's post-2023 regulatory repositioning – from confidentiality-based to compliance-based legitimacy – within a theory of financial-centre choice as an institutional complement for capital originating in weak-institution environments.

2. Theoretical Background

2.1 Institutional Uncertainty and the Primacy of Jurisdiction

The foundational claim of this paper is deliberately simple: for entrepreneurial wealth from institutionally uncertain environments, jurisdiction is not a secondary structuring issue. It is a primary determinant of wealth functionality. North (1990) establishes that institutions – formal rules, enforcement mechanisms, and cultural norms – reduce uncertainty by making economic behaviour predictable. Where enforcement is unreliable, long-horizon commitments become irrational. La Porta, Lopez-de-Silanes, Shleifer, and Vishny (1998) show that legal origin and investor-protection quality shape financial-market depth and capital allocation across jurisdictions. Williamson (2000) adds the transaction-cost perspective: every significant wealth commitment in an uncertain institutional environment carries embedded uncertainty about enforceability. This tends to produce delayed, defensive, or suboptimal structural choices.

Applied to emerging-market wealth, these arguments become particularly acute. Acemoglu and Robinson (2019) distinguish direct expropriation from indirect appropriation through selective law enforcement and administrative pressure. These are precisely the mechanisms described in post-Soviet political economy (Mau & Starodubrovskaya, 2001; Radygin & Entov, 2001). Khanna and Palepu (2010) conceptualise such deficiencies as institutional voids: the absence of market-supporting mechanisms that allow capital to be allocated efficiently and contracts to be honoured. Stephan, Uhlaner, and Stride (2026) refine this idea through a four-layer institutional hierarchy. Their framework shows that decision-making in void-characterised

environments is shaped not by one weakness, but by the interaction of formal regulatory gaps, constitutional instability, cultural risk attitudes, and informal enforcement norms.

Kazakhstan's empirical profile fits this theoretical characterisation. According to the World Justice Project (2023), Kazakhstan scores 0.47 in the Rule of Law Index, compared with Switzerland's approximately 0.83. This institutional distance is not just a ranking. It is a practical constraint on the structures that Kazakhstani families can rationally maintain domestically. The EBRD Transition Report (2024) confirms persistent gaps in property-rights protection, corporate governance, and judicial independence. The IMF (2024) also documents continuing exposure to hydrocarbon price cycles and currency risk. This vulnerability is reinforced by Kazakhstan's export structure: OECD (2024) shows that hydrocarbon products remain a dominant component of national exports, making large private fortunes indirectly exposed to overlapping commodity-price, currency, and political risks. For families whose fortunes emerged from this environment, international structuring is not a luxury or a tax strategy. It is the first and logically prior decision in wealth architecture.

2.2 Behavioural Finance: Home Bias, Loss Aversion, and Risk Normalisation

If institutional theory explains why international structuring is rational, behavioural finance explains why it still does not happen automatically. Kahneman and Tversky's (1979) prospect theory shows that outcomes are evaluated relative to a reference point, with losses weighted roughly 2.0 to 2.5 times more heavily than equivalent gains. For a founder whose reference point is ownership of an operating business, a diversified portfolio may feel like a loss of status, control, and professional identity – even when the financial value is unchanged. This is one reason why liquidity events do not automatically produce diversification.

French and Poterba (1991) define home bias as the systematic over-weighting of domestic assets. In Kazakhstan, some home bias is rational. Domestic entrepreneurs may genuinely possess information advantages and local network access. Yet the KASE Market Report (2024) indicates that domestic asset concentration in private portfolios exceeds what local expertise alone can justify. Coeurdacier and Rey (2013) show that home bias persists even among sophisticated investors because informational frictions, institutional familiarity, and perceived competence distort the evaluation of domestic versus foreign risk. Dlugosch, Horn, and Wang (2023) sharpen the point: investors do not simply prefer what is familiar; they actively avoid environments that feel difficult to understand or predict.

The Kazakhstani case therefore appears to involve a third mechanism beyond classical home bias: risk normalisation. Long-term exposure to currency volatility, institutional discretion, and informal enforcement creates cognitive schemas in which these structural risks are no longer perceived as risks. They become the ordinary texture of economic life. This matters for wealth transition, because the value of operating in a lower-risk jurisdiction is systematically underestimated when domestic risks have been normalised. The construct is consistent with the framing effects documented by Dlugosch et al. (2023) and with behavioural portfolio theory. Shefrin and Statman (2000) show that investors construct portfolios as layered mental accounts with reference points shaped by prior experience. Das, Markowitz, Scheid, and Statman (2010) further connect mental accounting to portfolio optimisation, showing that investors often define risk through account-specific thresholds rather than through a single mean-variance-efficient portfolio.

2.3 Socioemotional Wealth, Entrepreneurial Logic, and the Logic Gap

Behavioural bias is not the whole story. The reluctance of founders to adopt investor logic also reflects a deeper conflict between two institutional logics. Gómez-Mejía, Haynes, Núñez-Nickel, Jacobson, and Moyano-Fuentes (2007) show that family-controlled enterprises may accept risks that a purely financial shareholder would reject in order to preserve socioemotional wealth (SEW): the non-financial value derived from control, identity, social ties, and succession continuity.

Berrone, Cruz, and Gómez-Mejía (2012) operationalise SEW through the FIBER dimensions: family control and influence; family identification with the firm; binding social ties; emotional attachment; and renewal of family bonds through succession. Each dimension can resist institutionalised wealth management, because such management requires delegation, diversification, and documented governance procedures.

Thornton, Ocasio, and Lounsbury (2012) provide the organisational-theory vocabulary for this problem. Entrepreneurial and investor orientations can be understood as distinct institutional logics, each with its own values, decision heuristics, and performance metrics. Entrepreneurial logic prioritises concentrated commitment, opportunity exploitation, and direct control. Investor logic requires diversification, governance transparency, and probabilistic risk management. Besharov and Smith (2014) show that transitions between institutional logics create persistent cognitive and organisational conflict. The logic that was adaptive in the founding context does not disappear simply because conditions have changed. Kuratko, Fisher, and Audretsch (2021) identify the cognitive dimension of this persistence: entrepreneurial mindsets developed under uncertainty remain structurally stable. In post-liquidity settings, this may produce entrepreneurial mirroring – the tendency to reconcentrate capital in direct investments that reproduce the experience of business ownership.

The VUCA extensions of SEW theory developed by Gomez-Mejia, Mendoza-Lopez, Cruz, Duran, and Aguinis (2024) are especially relevant to the post-Soviet context. In volatile, uncertain, complex, and ambiguous environments, SEW can stabilise decision-making by creating a long-term orientation. At the same time, it can destabilise financial outcomes by subordinating diversification and governance to control preservation. The transition from this configuration to investor logic therefore requires more than information or financial education. It requires a structural intervention that changes the decision environment itself.

2.4 Wealth Management Architecture, Trust, and the Sequencing Logic

The entrepreneur-investor logic conflict can be addressed only if the decision environment changes. Zellweger (2017) treats professional asset structuring not as an auxiliary tax service but as a strategic institutional response. By placing wealth in legally robust structures – foundations, trusts, holding companies – families create contexts in which investor logic becomes more normal than exceptional. Maude (2006) adds that durable wealth-management relationships depend on institutional trust: the client's confidence that arrangements made today will be honoured across decades. Rivo-López, Villanueva-Villar, and Vaquero-García (2020) similarly argue that substantial family wealth cannot be managed through investment allocation alone. It requires the integration of investment management, governance structures, succession planning, and family objectives.

Giddens (1990) provides a useful distinction here: personal trust versus systemic trust. Personal trust is confidence in a specific individual's reliability. Systemic trust is confidence in the institutions, regulatory standards, and professional norms that govern a sector. For entrepreneurs whose experience has been shaped by low systemic trust and high reliance on personal networks, the move to institutionalised wealth management is not only technical. It is cognitive and cultural. Zucker (1986) shows that institutional-based trust is produced through certification systems, regulatory oversight, and standardised professional norms. These are precisely the features that distinguish established financial jurisdictions from informal alternatives.

DiMaggio and Powell (1983) provide the key sequencing insight: formal organisational structures do not merely record decisions already made. They create the conditions in which different decisions become possible. A foundation, family holding, or investment policy statement changes the context in which later investment and behavioural choices are made. Kotter (1996) makes the same point from change-management theory: durable behavioural transformation requires structural anchoring, otherwise informal habits reassert themselves. North (1990) gives the institutional-economics parallel: formal rules are prerequisites for productive economic

activity, not consequences of it. Together, these arguments support the sequencing proposition that structure must precede investment and cognitive reorientation.

2.5 Family Governance, Agency Theory, and Intergenerational Continuity

Family governance literature identifies governance architecture as a long-horizon determinant of wealth preservation. It does not replace investment performance, but it shapes whether good decisions can be sustained across generations. Jensen and Meckling (1976) establish the basic agency problem: wherever ownership and management are separated, or where several principals hold conflicting claims, governance mechanisms are needed to align incentives and limit opportunistic behaviour. Schulze, Lubatkin, Dino, and Buchholtz (2001) extend this logic to family firms. Altruistic relationships can produce distinctive moral hazards: founders may over-allocate resources to less capable family members, and governance structures may protect family cohesion at the expense of financial discipline. Formal mechanisms – investment committees, independent boards, documented investment policy statements, and externally facilitated family councils – therefore counteract agency costs specific to family wealth.

Zellweger (2017) argues that long-term wealth preservation depends less on any single period of investment performance than on structures capable of sustaining decision quality. Tagiuri and Davis (1996) identify the systemic source of many family-governance failures: family, ownership, and business overlap, but each system has its own logic and norms. No single personal relationship can reliably resolve these conflicts over time. Schickinger, Bierl, Leitterstorf, and Kammerlander (2023) add empirical nuance. Single family offices differ materially depending on generational stage and on whether the original operating business remains under family ownership.

Succession adds another layer. Cadieux (2007) shows that succession outcomes depend heavily on the predecessor's willingness to move from a directive role to a supportive one. This is difficult for founders whose identity is fused with operational control. Sharma, Chrisman, and Chua (2003) find that succession intentions are shaped by family norms, perceived behavioural control, and external social pressures. In first-generation Kazakhstani wealth, where succession traditions are still thin, intentions may remain unrealised even when they are sincerely stated. Steier (2001) shows that systemic trust in governance institutions mediates succession quality. Where such trust is absent, families substitute personal trust relationships. These may work within one generation, but they are fragile across generations.

3. The Swiss Financial Centre as Institutional Complement

Switzerland's role as an institutional anchor for Kazakhstani entrepreneurial wealth cannot be explained by generic references to stability or private banking tradition alone. The more precise argument is institutional complementarity. Switzerland offers institutional attributes that correspond directly to weaknesses in the country of wealth origin: legal predictability, treaty protection, monetary credibility, regulatory continuity, and a dense wealth-management infrastructure.

Switzerland manages approximately one quarter of the world's cross-border private wealth (Swiss Bankers Association, 2025). Zucman (2013) argues that this concentration reflects accumulated institutional legitimacy rather than regulatory arbitrage alone. Switzerland's share of global offshore assets remained structurally important even as information-exchange obligations expanded. The Global Financial Centres Index 39 (Z/Yen Partners & China Development Institute, 2026) confirms Switzerland's continuing position among leading financial centres. Compared with Luxembourg, Singapore, DIFC, and ADGM, Switzerland offers a distinctive combination: treaty protection for Kazakhstani capital, CHF monetary independence, deep private-banking expertise, and long regulatory continuity. Competing centres may offer some of these features, but the full combination is difficult to replicate.

The bilateral investment treaty between Switzerland and Kazakhstan, signed in 1994 and ratified in 1998 (Agreement between the Swiss Confederation and the Republic of Kazakhstan, 1994), provides the primary legal architecture for this complementarity. Gabriel (2013) characterises the treaty as transforming Swiss structuring from convenient into legally justified: it guarantees most-favoured-nation treatment, protects against direct and indirect expropriation, and grants access to ICSID arbitration. The subsequent updating of the double tax agreement (Kaeva, Zhursunov & Zhukov, 2023) extends this architecture to income treatment. The Astana International Financial Centre (AIFC), operating under English common law within Kazakhstan's civil-law jurisdiction, supported by a dedicated AIFC Court, and offering a Family Office Framework since July 2024 (AIFC Court, n.d.; Astana Financial Services Authority, 2024), may serve as a domestic institutional precursor. It gives families a staging environment in which governance structures can begin before capital is placed in international arrangements.

Swiss wealth management has also changed materially since 2023. Palan, Murphy, and Chavagneux (2010) argue that financial centres built on confidentiality face a repositioning imperative as multilateral information exchange expands. Switzerland's response – including the AML dispatch of 2024, LETA, the revised AMLA, CRS 2.0, and the Crypto-Asset Reporting Framework – marks a move from confidentiality-based to compliance-based institutional legitimacy (Swiss Federal Council, 2024, 2026). On 12 June 2026, the Federal Council set 1 October 2026 as the entry-into-force date for LETA and the revised AMLA. LETA establishes a centralised federal transparency register of beneficial owners accessible to designated authorities and AMLA-subject persons, but not to the general public (Swiss Federal Council, 2026). For Kazakhstani clients facing reputational and compliance risk, this shift may strengthen Switzerland's attractiveness rather than weaken it.

The currency dimension adds another layer of complementarity. Ranaldo and Söderlind (2010) show that Swiss franc-denominated assets attract safe-haven flows during periods of global stress, reflecting institutional quality and monetary-policy credibility. Many leading Swiss equity issuers generate most of their revenues outside Switzerland. They therefore provide globally diversified economic exposure within a CHF-denominated institutional framework. Core-Satellite portfolio construction using SMI, SLI, and SMIM constituents (SIX Group, 2022; Union Bancaire Privée, 2025) may help entrepreneurial families reduce idiosyncratic risk while retaining a familiar institutional and currency anchor. The CHF is not a substitute for diversification. It is a potential monetary and institutional anchor within the broader move from entrepreneurial concentration to investor logic.

4. The Swiss Wealth Integration Framework: Architecture and Propositions

4.1 Conceptual Architecture

The preceding synthesis shows that the institutionalisation of entrepreneurial capital is not a single decision. It is also not merely a portfolio-optimisation problem. It is a staged transformation across legal, behavioural, investment, and governance domains. Each stage depends, to some extent, on what has already been completed. The Swiss Wealth Integration Framework (SWIF) is proposed as a conceptual architecture for this process.

SWIF contains four ordered dimensions. Structure is the foundational dimension: the establishment of robust holding and ownership structures in a jurisdiction that provides enforceable property rights, treaty-based investment protection, and independent dispute resolution. Stability concerns behavioural and perceptual risk: risk normalisation, home bias, and the movement from personal to systemic trust. Investment operationalises investor logic within the structural and behavioural environment already created. It addresses portfolio construction, currency management, and entrepreneurial mirroring. Governance formalises intergenerational continuity through family governance documents, succession plans, investment policy statements, and next-generation education.

The sequence – Structure -> Stability -> Investment -> Governance – is not only pedagogical. It follows from the theory. Structure must precede Stability because behavioural recalibration is easier in a changed decision environment (DiMaggio & Powell, 1983; Kotter, 1996). Stability must precede Investment because portfolio decisions made under unaddressed bias often reproduce entrepreneurial mirroring instead of diversification. Investment policy must precede full Governance formalisation because governance documents are coherent only when investment logic, risk boundaries, and delegation principles have been clarified. At the same time, preliminary governance mechanisms, such as advisory mandates or decision protocols, may be needed earlier to prevent founder discretion from overriding the sequence. In this sense, the model is sequential but not mechanically rigid.

4.2 Theoretical Propositions

The six propositions below are derived from the literature synthesis. They are stated as testable propositions for empirical investigation, not as confirmed findings. This distinction is important: the article proposes a framework that the dissertation's interview-based research can later assess and refine.

No.	Proposition
P1	In institutionally volatile emerging markets, legal-institutional quality rather than risk-adjusted return expectations constitutes the primary determinant of international wealth structuring decisions among entrepreneurial families. Jurisdictional choice functions as a prerequisite for, rather than a component of, investment strategy.
P2	Switzerland may function as a dual institutional anchor for Kazakhstani entrepreneurial families – simultaneously providing legal-structural certainty through bilateral treaty architecture (BIT, DTA, ICSID access) and investment-strategic capability through CHF-denominated assets – a conjunction that competing financial centres find difficult to replicate in full.
P3	Long-term embeddedness in institutionally volatile environments generates a risk normalisation mechanism that operates as a behavioural mediator in wealth transition decisions, distorting the perceived risk-return profile of domestic versus international investments above and beyond the classical home bias documented in developed-market populations.
P4	Swiss equity exposure may serve as one investment mechanism through which entrepreneurial families operationalise investor logic within a trusted institutional and currency environment, combining defensive sector composition, global revenue diversification, and CHF monetary stability without implying that Swiss assets alone resolve the diversification challenge.
P5	Formal legal and institutional structures must be established prior to investment policy formulation and cognitive reorientation towards investor logic, because structural frameworks alter the decision environment within which behavioural change becomes sustainable across generations.

P6	Formal family governance architecture – encompassing investment policy documentation, family council mechanisms, agency-cost-limiting oversight structures, and succession planning – constitutes a core determinant of intergenerational wealth continuity, mediating the long-term effects of investment performance and founding-generation individual preferences.

Table 1. Theoretical Propositions of the Swiss Wealth Integration Framework. Source: compiled by the author.

5. Discussion

5.1 Theoretical Contributions

This paper contributes to entrepreneurial wealth-management research in three ways. First, it extends the institutional voids framework (Khanna & Palepu, 2010; Stephan et al., 2026) from firm-level FDI decisions to private wealth internationalisation. This establishes institutional voids as a household-level mechanism, not only a firm-level one. It also reframes private wealth internationalisation from emerging markets as a political-risk response, rather than only a tax or return strategy. This matters for the normative framing of offshore wealth research (Harrington, 2024; Zucman, 2013), because not all cross-border structuring has the same motivation.

Second, the concept of risk normalisation adds an emerging-market-specific channel to the home-bias literature. Classical home-bias theory emphasises informational frictions, familiarity preferences, and ambiguity aversion (Coeurdacier & Rey, 2013; Dlugosch et al., 2023). Risk normalisation adds another mechanism: the adaptation of cognitive risk schemas to environments of chronic institutional uncertainty. The result is an underestimation of domestic risk and an undervaluation of institutional-quality differentials. This is not simply unfamiliarity with foreign assets. It is a distortion of risk perception produced by long exposure to a specific institutional environment. For this reason, qualitative interviews are especially appropriate. Normalised risk is difficult to measure if respondents have never been asked to define the baseline against which they judge risk.

Third, SWIF offers an integrated model of how wealth-transformation decisions may need to be ordered. Its sequence is grounded in DiMaggio and Powell's (1983) institutional isomorphism theory, Kotter's (1996) change-management research, and North's (1990) institutional economics. The proposition that structure precedes investment and behavioural change challenges the common advisory tendency to begin with portfolio construction and address governance later.

5.2 Practical and Policy Implications

For advisors working with Kazakhstani and CIS entrepreneurial families, the central practical implication is sequencing. Advisors who begin with portfolio construction before legal structures and behavioural stabilisation are in place work against the logic of sustainable wealth transformation. The same applies when governance documents are formalised before investment logic, family objectives, and delegation boundaries have been clarified. The likely result is familiar: portfolio decisions are later overridden by founder discretion, or governance documents remain unused. Practitioner literature reports these patterns repeatedly (Dörig, n.d.; Minder, 2024). This does not imply one universal organisational solution. Family offices and related structures must be adapted to family goals, ownership configuration, and generational stage (Wessel et al., 2014).

For policy, the AIFC Family Office Framework (Astana Financial Services Authority, 2024) is theoretically significant. It creates a domestic precursor institutional environment that operates under English common law within Kazakhstan and is supported by a dedicated dispute-resolution architecture (AIFC Court, n.d.). In practical terms, it may allow entrepreneurial families to begin governance institutionalisation before full internationalisation. This could reduce the cognitive

distance involved in moving from personal trust to systemic trust in foreign institutions. Whether Kazakhstani families actually use the AIFC in this way remains an empirical question.

5.3 Limitations and Future Research

This paper is theoretical in nature. Its propositions are conceptual derivations, not empirically validated findings. The literature base is broad, but it still reflects the documented concentration of family business and wealth-management research in North America and Western Europe (Hayoz, Ge & De Massis, 2025). SEW theory, agency theory, and family-governance models may therefore require contextual adjustment when applied to post-Soviet entrepreneurial families. The risk normalisation construct also requires empirical operationalisation distinct from classical risk aversion and home-bias measures.

Future empirical work should use semi-structured interviews with Kazakhstani entrepreneurial families, Swiss private bankers, and AIFC-based wealth advisors to assess and refine the six propositions. Comparative research on other post-Soviet jurisdictions – Ukraine, Georgia, Azerbaijan – could test the generalisability of the institutional-complementarity argument. Finally, quantitative analysis, especially currency portfolio simulations using CHF/USD return decomposition, would help evaluate Proposition 4 on the investment-strategic role of Swiss equities in emerging-market family portfolios.

6. Conclusion

Entrepreneurial families in post-Soviet emerging markets face a wealth-management challenge that existing frameworks explain only in fragments. A more adequate account requires the integration of institutional economics, behavioural finance, socioemotional wealth theory, wealth-management trust research, financial-centre theory, and family governance. The Swiss Wealth Integration Framework (SWIF) offers such an integration. It models the institutionalisation of entrepreneurial capital as a sequential four-stage process grounded in six propositions.

The paper's principal contributions are threefold. It extends institutional voids to private wealth internationalisation. It identifies risk normalisation as a post-Soviet-specific behavioural mechanism distinct from classical home bias. And it grounds the sequencing proposition – that structure must precede investment and behavioural reorientation – in institutional isomorphism theory and organisational change research. Switzerland's post-2023 regulatory repositioning is interpreted not as a weakening of its advantage, but as a transition toward compliance-based institutional legitimacy. For the target client population, that legitimacy may be more durable and more valuable than the earlier confidentiality-based model.

The research gap is therefore practical as well as academic. A growing cohort of first-generation Kazakhstani entrepreneurs is approaching wealth transition without established succession traditions, deep family-office infrastructure, or sufficiently diversified capital bases. The SWIF framework is offered as a theoretical foundation for the empirical research programme needed to assess, refine, and, where necessary, revise it.

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Note: For reasons of space, the reference list above includes the sources most directly underpinning the paper's central propositions. The complete bibliography (62 sources) is available in the author's DBA dissertation manuscript.

Directions for Enhancing the Economic Efficiency of Employment Policy in Azerbaijan

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Abstract: Employment is one of the key macroeconomic indicators characterizing a country's level of socio-economic development, while also playing a crucial role in improving public welfare, reducing poverty, and ensuring social stability. In the contemporary period, structural transformations in the labour market, the acceleration of digitalization, global economic changes, and demographic trends have necessitated the development of employment policies based on new approaches. In recent years, Azerbaijan has implemented significant institutional and legal reforms aimed at regulating employment, increasing labour market transparency, reducing informal employment, enhancing the economic participation of socially vulnerable population groups, and promoting sustainable employment.
Keywords: employment, labour market, unemployment, informal employment, digitalization, employment policy, social protection, self-employment, Azerbaijani economy, labour relations.

Introduction

Employment is widely recognized as one of the fundamental indicators reflecting a country's level of economic development, social welfare, and the efficiency with which human capital is utilized. An efficiently functioning labour market constitutes not only a prerequisite for sustainable economic growth but also a key determinant of social stability, equitable income distribution, and improvements in the overall quality of life. In the context of globalization, rapid technological advancement, the expansion of the digital economy, and the transformation of labour relations, employment policy has undergone significant conceptual changes. Traditional employment models are increasingly being replaced by more flexible labour market mechanisms, new occupations are emerging, while others are gradually becoming obsolete. Consequently, contemporary employment policy extends beyond the objective of reducing unemployment and has become an important instrument for fostering human capital development, enhancing labour productivity, and strengthening national economic competitiveness. In recent years, the Republic of Azerbaijan has attached particular importance to the development of employment relations within the broader framework of economic diversification. Reducing dependence on the oil sector, promoting the development of non-oil industries, and creating sustainable employment opportunities have become strategic priorities of the country's socio-economic policy. To achieve these objectives, a number of significant institutional and legislative reforms have been implemented, including the adoption of the revised *Law on Employment*, the expansion of the activities of the State Employment Agency, the introduction of the Electronic Labour Contract System, the implementation of active labour market programmes, and the extension of self-employment initiatives. These reforms have contributed to strengthening labour market institutions, increasing transparency, and improving the accessibility and effectiveness of employment services. According to official statistics, by the end of 2024, Azerbaijan's economically active population had reached approximately 5.3 million people, while the number of employed persons approached 5 million, resulting in an unemployment rate of 5.8%. Although these

indicators demonstrate the overall stability of the labour market, several structural challenges remain unresolved. These include the persistence of informal employment, relatively high unemployment among young people, regional disparities in employment opportunities, and the mismatch between the qualifications produced by the education system and the skills demanded by the labour market. Such challenges indicate that quantitative improvements in employment must be accompanied by qualitative enhancements in labour market performance. Employment regulation should therefore be regarded not only as an economic policy instrument but also as a fundamental component of social policy. Developments in the labour market have direct implications for household incomes, the financial sustainability of the social protection system, and the fiscal capacity of the state. In particular, the widespread prevalence of informal employment reduces social insurance contributions, weakens the long-term sustainability of the pension system, narrows the tax base, and limits public revenues. Consequently, the formalization of employment relations and the digitalization of labour market governance have become key priorities of public policy in Azerbaijan. The primary objective of this article is to provide a comprehensive scientific assessment of the current state of employment regulation in Azerbaijan, evaluate the outcomes of the government's employment policy, identify the major structural challenges affecting the labour market, and propose evidence-based policy recommendations aimed at enhancing the economic efficiency of employment policy. The research is based on a comparative analysis of national legislation, official statistical data, reports published by international organizations, and relevant contemporary academic literature.

Main Body

1. Theoretical and Legal Foundations of Employment Regulation

In economic theory, employment refers to the engagement of the working-age population in socially productive activities and is regarded as one of the fundamental components of macroeconomic equilibrium. While representatives of the classical school of economics argued that employment is primarily regulated through market mechanisms and the interaction of labour supply and demand, the Keynesian approach, which emerged in the twentieth century, emphasized the necessity of government intervention to maintain full employment and macroeconomic stability. Contemporary economic theories further broaden this perspective by linking employment to human capital development, innovation capacity, institutional quality, labour market flexibility, and sustainable economic growth. Accordingly, employment is no longer viewed solely as a labour market outcome but also as a strategic determinant of national competitiveness and long-term economic development. The legal framework governing employment relations in the Republic of Azerbaijan consists primarily of the Labour Code of the Republic of Azerbaijan, the Law on Employment, the Employment Strategy of the Republic of Azerbaijan (2020–2025), and other legislative and regulatory acts concerning labour relations and social protection. These legal instruments establish the institutional foundations of the national employment policy, regulate labour relations, provide legal guarantees for unemployed individuals, define the implementation mechanisms of active labour market programmes, and ensure equal access to employment opportunities. Their adoption has significantly contributed to improving labour market governance, enhancing institutional coordination, and strengthening the legal protection of employees and job seekers. The principal institutional responsibility for implementing employment policy rests with the Ministry of Labour and Social Protection of Population and its subordinate State Employment Agency. These institutions are responsible for monitoring labour market developments, registering job seekers, organizing vocational training programmes, conducting employment fairs, implementing active labour market measures, and coordinating self-employment initiatives. In recent years, the expansion of e-government services has substantially transformed the delivery of employment services. The digital integration of employment-related services has simplified administrative procedures, increased transparency,

reduced bureaucratic barriers, and improved citizens' access to labour market information and public employment services. One of the major priorities of Azerbaijan's employment policy has been the expansion of active labour market programmes. These programmes include vocational education and training, career guidance services, public works programmes, employment fairs, entrepreneurship support measures, and self-employment initiatives. Among these instruments, the self-employment programme occupies a particularly important position due to its contribution to promoting micro-entrepreneurship among socially vulnerable population groups. Within the framework of this programme, beneficiaries receive productive assets, equipment, and other start-up resources necessary to establish sustainable income-generating activities. By supporting entrepreneurial initiatives rather than providing temporary financial assistance, the programme aims to create long-term employment opportunities and reduce dependence on social transfers. According to official statistics, approximately 17,000 individuals benefited from the self-employment programme in 2024, demonstrating the government's continued commitment to strengthening inclusive labour market participation and promoting sustainable economic empowerment.

2. Statistical Analysis of the Current Employment Situation in Azerbaijan

In recent years, the implementation of comprehensive macroeconomic reforms and economic diversification policies in the Republic of Azerbaijan has contributed to positive developments in the labour market. The expansion of the non-oil sector, government support for entrepreneurship, large-scale infrastructure investments, and the implementation of regional development programmes have collectively facilitated the creation of new employment opportunities. Nevertheless, despite these favourable trends, several structural challenges continue to affect the quality and sustainability of employment. These challenges include the persistence of informal employment, regional disparities in labour market opportunities, the mismatch between vocational education and labour market demand, and relatively high unemployment among young people. According to the State Statistical Committee of the Republic of Azerbaijan, the economically active population reached approximately 5.3 million by the end of 2024, while nearly 5 million individuals were employed, resulting in an unemployment rate of 5.8%. Although these indicators suggest overall labour market stability, aggregate unemployment figures alone do not provide a comprehensive assessment of labour market performance. A thorough evaluation also requires consideration of qualitative indicators such as labour productivity, employment quality, the level of formalization of labour relations, sectoral employment distribution, wage dynamics, and workforce skills. Statistical data for mid-2024 indicate that the total number of wage employees amounted to approximately 1.749 million. Of these, around 893 thousand were employed in the public sector, while approximately 856 thousand worked in the private sector. These figures demonstrate that the public sector continues to occupy a dominant position within Azerbaijan's labour market. In contrast, in most developed market economies, the majority of employment is generated by the private sector. The relatively high share of public employment in Azerbaijan reflects the structural characteristics of the national economy, particularly the significant role of publicly financed sectors such as education, healthcare, public administration, and defence. An analysis of employment by economic activity further reveals the structural composition of the labour market. The education sector accounts for approximately 18.9% of total employment, followed by wholesale and retail trade together with motor vehicle repair activities at 18.6%. Industrial activities represent 12.8% of total employment, while healthcare and social services account for approximately 8.4%. Construction, public administration, defence, transportation, and other service industries also constitute important sources of employment. This sectoral structure indicates the predominance of service-based activities within the national economy while simultaneously demonstrating that knowledge-intensive, high-technology, and innovation-driven industries continue to account for a relatively limited share of total

employment. Another significant development has been the continuous increase in the number of registered labour contracts. The introduction of the Electronic Labour Contract Notification System, combined with strengthened labour inspection mechanisms and enhanced administrative oversight, has substantially contributed to the formalization of employment relations. Between 2018 and 2025, the number of registered labour contracts increased by more than 40%, with the majority of newly registered contracts originating from the private sector. This trend reflects the effectiveness of government policies aimed at reducing informality, increasing transparency, and improving compliance with labour legislation. Despite these positive developments, informal employment remains one of the most significant structural weaknesses of Azerbaijan's labour market.

3. Development Directions for Women's and Youth Employment

From the perspective of achieving inclusive economic growth, increasing the participation of women and young people in the labour market has become one of the fundamental priorities of employment policy. International experience demonstrates that higher labour force participation among women contributes directly to economic growth by expanding the productive workforce, increasing household incomes, reducing poverty, and enhancing overall social welfare. Moreover, greater gender equality in employment promotes more efficient utilization of human capital, strengthens labour productivity, and improves long-term economic competitiveness. Recognizing these benefits, the Government of Azerbaijan has implemented a range of policy measures in recent years aimed at promoting gender equality, strengthening women's economic independence, and expanding equal access to employment opportunities. According to official statistics, approximately 2.2 million women were employed in Azerbaijan in 2024, while the economically active female population reached around 2.4 million. Despite this progress, women continue to face significant challenges in labour market participation, particularly due to the prevalence of informal employment. Approximately 28% of employed women work in the informal sector, limiting their access to social insurance, pension benefits, and other labour rights guaranteed under formal employment relationships. To address these issues, various initiatives have been introduced, including the establishment of Women's Resource Centres, support programmes for female entrepreneurship, preferential financing mechanisms for women-owned businesses, and self-employment projects specifically targeting socially vulnerable women. These initiatives have not only expanded women's participation in economic activity but have also contributed to regional development and poverty reduction by encouraging entrepreneurial activity and income generation among disadvantaged groups. Youth employment represents another critical component of Azerbaijan's labour market policy. Young people constitute one of the most vulnerable groups in the labour market due to limited work experience, skill mismatches, and the continuously changing requirements of employers. Each year, more than one hundred thousand young people enter the labour market, creating a growing demand for sustainable and high-quality employment opportunities. At the same time, the existing education and vocational training systems have not always fully aligned with the evolving needs of the economy, contributing to relatively higher unemployment rates among young people. Official statistics indicate that the unemployment rate among individuals aged 15–24 remained considerably higher than the national average in 2024, highlighting the persistence of structural barriers to youth employment. In response, the State Employment Agency has expanded vocational training programmes, career guidance services, employment fairs, internship schemes, and self-employment initiatives designed specifically for young job seekers. Thousands of young people have participated in vocational education programmes and received productive assets to establish their own businesses, thereby improving their employability and entrepreneurial capacity. Nevertheless, further policy improvements remain necessary. Strengthening cooperation between higher education institutions and employers, expanding dual education systems,

integrating practical training into university curricula, and supporting innovation-driven start-ups are likely to enhance the transition of graduates from education to employment while simultaneously improving labour market efficiency and productivity.

4. The Role of Digitalization in Employment Regulation

The rapid development of the digital economy has fundamentally transformed labour markets worldwide by creating new forms of employment, increasing labour market flexibility, and improving the efficiency of employment services. The application of modern information and communication technologies has significantly enhanced the administration of labour relations, making employment governance more transparent, efficient, and responsive to labour market dynamics. In Azerbaijan, digital transformation has become one of the key pillars of employment policy, contributing substantially to the modernization of labour market institutions and the formalization of employment relationships. One of the most significant digital reforms has been the introduction of the Electronic Labour Contract Notification System, which enables the electronic registration and monitoring of labour contracts. This system has played a crucial role in reducing informal employment by ensuring greater transparency in employer–employee relations and facilitating more effective enforcement of labour legislation. In parallel, the Employment Subsystem has expanded citizens' access to employment services by allowing job seekers to register online, search for vacancies, receive career guidance, and apply for government employment programmes through digital platforms. By the beginning of 2025, the number of electronically registered labour contracts had exceeded 2.1 million, while hundreds of thousands of job seekers had registered through the Employment Subsystem. These developments demonstrate the government's commitment to building a modern, technology-driven labour market management system capable of responding more effectively to changing labour market conditions. However, the impact of digitalization extends well beyond improvements in administrative efficiency. The widespread adoption of artificial intelligence, big data analytics, automation technologies, cloud computing, and digital platforms is fundamentally reshaping labour demand by creating entirely new occupations while simultaneously transforming or eliminating many traditional professions. Consequently, digital skills have become one of the most valuable forms of human capital and are increasingly regarded as a key determinant of employability and labour market competitiveness. In this context, employment policy should not merely focus on adapting to technological change but should actively support the development of digital competencies across all segments of the workforce. Investments in digital education, lifelong learning programmes, reskilling and upskilling initiatives, and innovation-oriented vocational training are therefore essential for ensuring that the labour force remains competitive in an increasingly technology-driven global economy. Accordingly, the continued development of human capital through digital transformation should remain a strategic priority of Azerbaijan's employment policy, contributing not only to higher labour productivity but also to sustainable economic growth and long-term national competitiveness.

5. Economic and Social Consequences of Informal Employment

Informal employment is widely recognized as one of the most significant structural challenges facing contemporary labour markets. It refers to employment relationships that are not formalized in accordance with legal regulations, including the absence of employment contracts, non-payment of social insurance contributions, and failure to comply fully with tax obligations. As in many developing economies, informal employment remains a persistent structural issue within Azerbaijan's labour market. Although substantial institutional and legislative reforms have been implemented in recent years to promote labour market formalization, further policy efforts are still required to significantly reduce the scale of informal employment and strengthen labour market governance. One of the most serious consequences of informal employment is its adverse impact on the social protection system. Individuals employed without formal labour contracts

generally do not make social insurance contributions, preventing them from accumulating adequate pension entitlements and limiting their eligibility for unemployment benefits, disability insurance, healthcare coverage, and compensation for occupational accidents. Consequently, informal workers face greater economic vulnerability and a higher risk of poverty throughout their working lives and during retirement. In the long run, the widespread prevalence of informal employment contributes to growing social inequality by reducing access to comprehensive social security mechanisms and weakening the inclusiveness of the welfare system. Another significant consequence concerns the fiscal capacity of the state. Since informal workers and employers frequently evade income tax and social insurance obligations, government revenues are substantially reduced. A narrower tax base constrains public expenditure on education, healthcare, infrastructure development, and social welfare programmes, thereby limiting the government's ability to finance long-term socio-economic development. Furthermore, the existence of a large informal sector complicates the accurate measurement of economic activity, leading to distortions in official labour market statistics and reducing the effectiveness of evidence-based economic policymaking. The widespread use of informal labour arrangements also weakens the protection of workers' rights. Employees working without formal contracts are often excluded from legally guaranteed benefits, including paid annual leave, sick leave, occupational health and safety protections, minimum wage guarantees, and legal mechanisms for resolving labour disputes. As a result, informal workers become increasingly dependent on unilateral decisions made by employers and face significantly greater employment insecurity. The absence of formal contractual relationships undermines labour standards and contributes to precarious working conditions that negatively affect both individual welfare and overall labour market efficiency. Informal employment also has important implications for labour productivity and human capital development. Enterprises operating outside the formal economy generally invest less in employee training, professional development, technological modernization, and innovation. Consequently, workers employed in the informal sector often experience slower skill development and lower productivity growth, reducing the overall competitiveness of the economy. Since modern economic development increasingly depends on highly skilled, innovative, and productive human capital, the persistence of informal employment represents a significant obstacle to sustainable economic growth and structural transformation.

These considerations demonstrate that reducing informal employment should not be viewed solely as a component of social policy but rather as an integral element of fiscal policy, tax administration, labour market regulation, and national economic development strategy. Achieving this objective requires the implementation of comprehensive policy measures, including tax incentives for employers to formalize employment relationships, further expansion of the Electronic Labour Contract System, strengthening labour inspection mechanisms, improving regulatory enforcement, and enhancing public awareness regarding labour rights and social insurance obligations. Such measures would contribute to greater labour market transparency, increased fiscal sustainability, stronger social protection, and improved economic competitiveness.

6. Major Challenges and Future Prospects for Employment Regulation in Azerbaijan

Despite the positive developments observed in Azerbaijan's labour market during recent years, a number of structural challenges continue to hinder the effectiveness and long-term sustainability of employment policy. Addressing these issues is essential for improving labour market efficiency, increasing productivity, and ensuring inclusive economic growth. One of the most significant challenges is the mismatch between the education system and labour market demand. Graduates of higher education institutions and vocational schools frequently possess qualifications that do not correspond to the skills required by employers, resulting in simultaneous labour shortages in

certain sectors and unemployment among qualified graduates. This structural imbalance reduces labour market efficiency and weakens the country's human capital utilization. To overcome this challenge, Azerbaijan should establish a comprehensive labour market forecasting system capable of identifying future skill requirements, strengthen cooperation between universities and businesses, expand work-based learning opportunities, and further develop the dual education model that combines academic instruction with practical workplace experience. A second major challenge concerns regional disparities in employment opportunities. Economic activity remains heavily concentrated in Baku and the Absheron economic region, resulting in significant geographical imbalances in labour demand. Many regions continue to experience limited industrial activity, insufficient infrastructure, constrained investment opportunities, and relatively low job creation rates. Consequently, internal labour migration toward the capital continues to intensify. Promoting balanced regional development through the establishment of industrial parks, agro-parks, logistics centres, technology hubs, and innovation clusters would contribute to creating sustainable employment opportunities outside the capital while supporting broader regional economic diversification. Another increasingly important challenge is preparing the workforce for the digital transformation of the labour market. The rapid advancement of artificial intelligence, automation, robotics, and digital platforms is expected to transform or replace many existing occupations while simultaneously creating demand for new digital professions. Under these conditions, continuous learning, lifelong education, digital literacy, and workforce reskilling have become essential components of modern employment policy. Strengthening digital competencies across all age groups will enhance labour productivity, improve adaptability to technological change, and increase the competitiveness of Azerbaijan's human capital in the global economy. In addition to these structural challenges, enhancing the economic efficiency of employment policy requires greater emphasis on employment quality rather than merely increasing the number of jobs. Future policy should prioritize the creation of high-productivity, innovation-oriented, and knowledge-intensive employment capable of generating sustainable income growth and long-term economic resilience. This objective can be achieved through stronger support for entrepreneurship, expanded investment in research and innovation, improved labour market flexibility, and the development of a highly skilled workforce capable of meeting the demands of a modern digital economy.

7. Directions for Improving the Economic Efficiency of Employment Policy in Azerbaijan

Under contemporary conditions of economic development, the primary objective of employment policy extends beyond merely reducing unemployment. It increasingly focuses on establishing a sustainable labour market capable of supporting economic growth, enhancing labour productivity, and ensuring the efficient utilization of human capital. Consequently, improving the economic efficiency of employment policy in Azerbaijan requires the implementation of comprehensive institutional, fiscal, structural, and innovation-oriented reforms. Although substantial legislative and institutional changes have been introduced in recent years to modernize labour market governance, the ongoing processes of global economic transformation, digitalization, demographic change, and rapidly evolving labour market skill requirements necessitate the continuous adaptation and improvement of existing employment policies. The economic efficiency of employment policy largely depends on the optimal allocation of labour resources and the continuous improvement of labour productivity. In this regard, increased investment in human capital remains one of the most effective policy instruments for achieving sustainable economic development. Modern labour markets increasingly demand highly skilled workers equipped with advanced technical, digital, and analytical competencies. Therefore, strengthening vocational education and training systems, aligning educational curricula with labour market needs, and fostering closer cooperation between educational institutions and employers are essential prerequisites for enhancing workforce competitiveness. Existing structural mismatches indicate

that Azerbaijan's vocational education system does not yet fully satisfy the growing demand for qualified specialists in high-technology industries, the digital economy, renewable energy, logistics, advanced manufacturing, and innovation-driven sectors. Consequently, updating vocational education programmes based on medium- and long-term labour market forecasting, expanding dual education models that combine theoretical instruction with practical workplace experience, and promoting lifelong learning initiatives would significantly improve both labour market adaptability and employment policy effectiveness. Another strategic priority involves reducing informal employment and promoting the formalization of labour relations. Expanding the coverage of the Electronic Labour Contract Notification System, improving tax administration and social insurance mechanisms, and introducing fiscal incentives for small and medium-sized enterprises to formalize employment relationships could substantially reduce the size of the informal economy. Such measures would increase social insurance contributions, strengthen the fiscal sustainability of public finances, and improve compliance with labour legislation. At the same time, the formalization of employment would enhance workers' social protection, strengthen legal guarantees, improve working conditions, and contribute to higher labour productivity through greater investment in employee training and professional development. A more transparent labour market would also improve the accuracy of official employment statistics and facilitate evidence-based policymaking. Increasing the economic efficiency of employment policy also requires a more balanced utilization of regional economic potential. Currently, the concentration of employment opportunities in Baku and the Absheron economic region has contributed to persistent regional socio-economic disparities and increased internal migration. Addressing these imbalances requires targeted regional development policies aimed at stimulating private investment, industrial diversification, and entrepreneurship outside the capital region. The establishment of industrial parks, agro-parks, logistics centres, tourism clusters, and innovation hubs can accelerate job creation while supporting sustainable regional economic development. In particular, large-scale reconstruction programmes implemented in Azerbaijan's liberated territories—including the development of "Smart City" and "Smart Village" projects, renewable energy zones, and modern transport infrastructure—provide a unique opportunity to establish a new model of high-productivity employment based on advanced technologies, environmental sustainability, and digital infrastructure. These initiatives are expected to create substantial employment opportunities while simultaneously strengthening the long-term competitiveness of regional economies. The continued expansion of the digital economy represents another strategic direction for increasing the effectiveness of employment policy. Digital labour market platforms, electronic employment services, artificial intelligence-based job matching systems, and big data technologies reduce information asymmetries between employers and job seekers, thereby improving the allocation of labour resources and increasing labour market efficiency. Furthermore, digital transformation has fundamentally altered the structure of labour demand by generating entirely new occupations and transforming traditional professions. As a result, digital literacy, advanced technological competencies, and continuous professional development have become essential determinants of employability in the modern economy. Public policy should therefore prioritize investments in digital education, workforce reskilling, and lifelong learning to ensure that employees possess the competencies required in an increasingly technology-intensive labour market. Fiscal policy also plays a crucial role in enhancing the economic efficiency of employment policy. Investment incentives, tax preferences, wage subsidies, and public-private partnership mechanisms can encourage business expansion and stimulate the creation of sustainable employment opportunities, particularly within the non-oil sector. Fiscal support directed toward labour-intensive industries, innovative start-ups, high-technology manufacturing, export-oriented enterprises, and research-intensive businesses can simultaneously increase labour productivity and expand the availability of high-quality jobs. Moreover, strengthening

entrepreneurship support programmes and facilitating access to finance for small and medium-sized enterprises can further diversify employment opportunities while improving economic resilience. An equally important aspect of an efficient employment policy is the promotion of inclusive labour market participation. Expanding active labour market programmes that support women, young people, persons with disabilities, internally displaced persons, and other vulnerable social groups contributes not only to greater labour force participation but also to more efficient utilization of national human capital. Inclusive employment policies reduce income inequality, strengthen social cohesion, and increase the productive capacity of the economy by integrating previously underutilized labour resources into formal economic activity.

Conclusion

The findings of this study indicate that the institutional and legislative reforms implemented in Azerbaijan over recent years have contributed significantly to improving labour market performance and strengthening the country's employment governance framework. The adoption of the revised *Law on Employment*, the introduction of the Electronic Labour Contract Notification System, the expansion of the activities of the State Employment Agency, the implementation of active labour market programmes, and the acceleration of digital transformation have collectively enhanced labour market transparency, promoted the formalization of employment relationships, and improved access to employment services. These reforms have also strengthened the institutional capacity of public employment services and created more favourable conditions for sustainable labour market development. Despite these achievements, the analysis demonstrates that several structural challenges continue to limit the overall effectiveness of employment policy. The persistence of informal employment, regional disparities in employment opportunities, relatively high unemployment among young people, the mismatch between educational outcomes and labour market requirements, and the profound changes associated with digital transformation remain significant obstacles to improving labour market efficiency. These challenges highlight the necessity of continuously adapting employment policy to changing economic conditions and technological developments while strengthening institutional coordination and evidence-based policymaking. The study suggests that future employment policy should focus not only on increasing the quantity of employment but also on improving its quality. Sustainable economic development requires the creation of productive, innovative, competitive, and socially protected employment capable of generating long-term economic value. Achieving this objective will require greater investment in human capital, modernization of vocational education and training systems, wider integration of digital technologies into labour market governance, development of new occupations associated with the green economy and the digital economy, and further reduction of informal employment through effective institutional and fiscal measures. At the same time, strengthening cooperation between educational institutions, employers, government agencies, and private-sector stakeholders will be essential for improving workforce adaptability and labour market responsiveness. Furthermore, enhancing the economic efficiency of employment policy should be viewed as an integral component of Azerbaijan's broader strategy for sustainable economic growth and economic diversification. Policies aimed at increasing labour productivity, encouraging innovation, promoting entrepreneurship, supporting regional development, and improving workforce skills will simultaneously strengthen national competitiveness and increase the resilience of the labour market to future economic shocks. In this context, employment policy should increasingly emphasize lifelong learning, digital competencies, innovation-driven job creation, and inclusive labour market participation as key drivers of long-term economic prosperity. In conclusion, effective employment regulation represents one of the fundamental pillars of Azerbaijan's sustainable socio-economic development. A modern, inclusive, and productive labour market not only contributes to higher

living standards and improved social welfare but also enhances the efficient utilization of human capital and strengthens the country's long-term economic competitiveness.

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Pedagogical Sciences

ПРИМЕНЕНИЕ ГЕНЕРАТИВНОГО ИСКУССТВЕННОГО ИНТЕЛЛЕКТА В ФОРМИРОВАНИИ ПРОФЕССИОНАЛЬНЫХ КОМПЕТЕНЦИЙ БУДУЩИХ ПЕДАГОГОВ-ПСИХОЛОГОВ

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Аннотация. В статье рассматриваются методические возможности применения генеративного искусственного интеллекта в процессе формирования профессиональных компетенций будущих педагогов-психологов. Обоснована целесообразность использования генеративных языковых моделей как средства отработки диагностической, консультативной и коррекционно-развивающей компетенций. Описаны три методических приёма - анализ учебных кейсов, симуляция консультативных диалогов и генерация коррекционно-развивающих сценариев, разработанный диагностический инструментарий и уровневые дескрипторы. Представлен опыт организации опытно-экспериментальной работы с участием 30 магистрантов второго курса образовательной программы «Педагогика и психология» в период с сентября по декабрь 2025 года. Приведена динамика уровней и средних показателей сформированности профессиональных компетенций, подтверждённая методами статистического анализа, результаты анализа по подгруппам и рефлексивного опроса. Обозначены дидактические и этические ограничения применения технологии.

Ключевые слова: генеративный искусственный интеллект, педагог-психолог, профессиональные компетенции, диагностика, психологическое консультирование, коррекционно-развивающая работа, учебный кейс, симуляция диалога, высшее образование.

Цифровая трансформация системы высшего образования Республики Казахстан актуализирует поиск новых средств профессиональной подготовки специалистов помогающих профессий. Особое место среди них занимает подготовка педагогов-психологов, деятельность которых предполагает владение диагностическими, консультативными и коррекционно-развивающими компетенциями. Формирование данных компетенций традиционно требует значительного объёма практики, обратной связи и разбора большого числа профессиональных ситуаций, что в условиях ограниченного аудиторного времени и доступа к реальным клиентам представляет существенную методическую проблему.

Генеративный искусственный интеллект (далее - генеративный ИИ), основанный на больших языковых моделях, открывает возможности для частичного решения этой проблемы. Способность таких систем порождать связные тексты, вести диалог,

моделировать поведение собеседника и формулировать содержательную обратную связь позволяет использовать их в качестве учебного инструмента для отработки профессиональных действий будущего педагога-психолога в безопасной, воспроизводимой и управляемой среде.

Целью настоящей работы является описание и апробация методики применения генеративного ИИ для формирования профессиональных компетенций будущих педагогов-психологов. В основу методики положены три взаимосвязанных приёма: анализ учебных кейсов, симуляция консультативных диалогов и генерация коррекционно-развивающих сценариев.

Теоретические предпосылки

Под профессиональными компетенциями педагога-психолога в исследовании понимается совокупность знаний, умений и готовностей, обеспечивающих эффективное выполнение диагностической, консультативной и коррекционно-развивающей деятельности. Диагностическая компетенция предполагает умение выдвигать и проверять психолого-педагогические гипотезы, подбирать методики, интерпретировать результаты. Консультативная компетенция связана с установлением контакта, ведением беседы, формулированием вопросов и рефлексией собственной позиции. Коррекционно-развивающая компетенция включает проектирование программ помощи, подбор упражнений и оценку их эффективности.

Генеративный ИИ в образовательном процессе рассматривается не как замена преподавателя или супервизора, а как дополнительное средство, расширяющее пространство учебной практики. Языковая модель выступает одновременно генератором учебного материала, партнёром по диалогу и источником вариативной обратной связи, что соответствует деятельностному и практико-ориентированному подходам к подготовке специалистов.

Организация и методы работы

Опытно-экспериментальная работа проводилась на базе Кокшетауского университета имени Абая Мырзахметова с сентября по декабрь 2025 года и включала три последовательных этапа. Общая логика и содержание этапов представлены в таблице 1.

Таблица 1 - Этапы и содержание опытно-экспериментальной работы

Этап	Сроки	Основное содержание работы	Форма диагностики
Подготовительный	сентябрь 2025 г.	Входная диагностика, знакомство с инструментами генеративного ИИ, инструктаж по этике и конфиденциальности	Входное тестирование
Основной	октябрь – ноябрь 2025 г.	Реализация трёх приёмов: анализ учебных кейсов, симуляция консультативных диалогов, генерация коррекционно-развивающих сценариев	Текущая экспертная оценка заданий
Заключительный	декабрь 2025 г.	Итоговая диагностика, рефлексивный опрос, статистическая обработка результатов	Итоговое тестирование, анкетирование

В работе приняли участие 30 магистрантов второго курса образовательной программы «Педагогика и психология». Обобщённая характеристика выборки представлена в таблице 2.

Таблица 2 - Характеристика участников исследования (n = 30)

Характеристика выборки	Значение
Общее число участников	30 человек
Уровень и курс обучения	магистратура, 2 курс
Образовательная программа	«Педагогика и психология»
Форма обучения	очная
Состав по полу (жен./муж.)	22 / 8
Средний возраст	24,3 года
Имели опыт работы с генеративным ИИ	11 человек (36,7 %)

Методика реализовывалась в рамках практических занятий и самостоятельной работы обучающихся. Её содержание, соотнесённое с формируемыми компетенциями и объёмом учебных заданий, приведено в таблице 3.

Таблица 3 - Содержание методики применения генеративного ИИ

Приём	Формируемая компетенция	Содержание учебных заданий	Кол-во заданий
Анализ учебных кейсов	Диагностическая	Генерация психолого-педагогических ситуаций, выдвижение гипотез, подбор методик, интерпретация	8
Симуляция консультативных диалогов	Консультативная	Диалог с моделью в роли клиента, структурированная обратная связь по технике беседы	6
Генерация коррекционно-развивающих сценариев	Коррекционно-развивающая	Проектирование программ помощи, отбор упражнений, критическая доработка	6

Первый приём - анализ учебных кейсов. Магистранты формулировали запросы к языковой модели на генерацию описаний психолого-педагогических ситуаций различной сложности, после чего самостоятельно выдвигали диагностические гипотезы, подбирали методики и сопоставляли собственный анализ с вариантами, предложенными системой.

Второй приём - симуляция консультативных диалогов. Языковой модели задавалась роль условного клиента с определённым запросом и эмоциональным состоянием, а магистрант выступал в роли консультирующего специалиста, получая затем структурированную обратную связь по технике беседы.

Третий приём - генерация коррекционно-развивающих сценариев. На основе описанного случая магистранты совместно с системой разрабатывали варианты коррекционно-развивающих программ, отбирали упражнения и критически дорабатывали предложенные варианты с опорой на профессиональные требования.

Оценка уровня сформированности компетенций осуществлялась на основе уровневых дескрипторов, представленных в таблице 4. Уровень определялся экспертами по трёхуровневой шкале и переводился в баллы по десятибалльной шкале.

Таблица 4 - Уровневые дескрипторы сформированности компетенций

Компонент	Низкий уровень	Средний уровень	Высокий уровень
Диагности-ческий	Гипотезы поверхностны, методики подобраны без обоснования	Гипотезы в целом верны, интерпретация с отдельными ошибками	Гипотезы точны, методики обоснованы, интерпретация корректна
Консульта-тивный	Контакт неустойчив, вопросы закрытые, фокус беседы теряется	Контакт установлен, техника вопросов частично освоена	Контакт устойчив, вопросы уместны, фокус беседы удерживается
Коррекци-онно-развива-ющий	Программа фрагментарна, упражнения слабо связаны с целью	Программа логична, часть упражнений требует доработки	Программа целостна, упражнения адекватны, результаты реалистичны

Важным условием работы было обязательное критическое осмысление продуктов, полученных с помощью генеративного ИИ: обучающиеся не принимали ответы системы как окончательные, а проверяли и корректировали их.

Результаты и обсуждение

Сравнение результатов входной и итоговой диагностики показало положительную динамику по всем трём компонентам профессиональной компетентности. Распределение обучающихся по уровням в абсолютных значениях и процентах представлено в таблице 5.

Таблица 5 - Динамика уровней сформированности компетенций (n = 30)

Компонент компетентности	Высокий чел. / %	Средний чел. / %	Низкий чел. / %
Диагностический (до)	5 / 16,7	15 / 50,0	10 / 33,3
Диагностический (после)	14 / 46,7	13 / 43,3	3 / 10,0
Консультативный (до)	4 / 13,3	14 / 46,7	12 / 40,0
Консультативный (после)	12 / 40,0	15 / 50,0	3 / 10,0
Коррекционно-развивающий (до)	3 / 10,0	13 / 43,3	14 / 46,7
Коррекционно-развивающий (после)	11 / 36,7	15 / 50,0	4 / 13,3

Как видно из таблицы 5, доля обучающихся с высоким уровнем диагностической компетенции возросла с 16,7 % до 46,7 %, консультативной - с 13,3 % до 40,0 %, коррекционно-развивающей - с 10,0 % до 36,7 %. Одновременно существенно сократилась доля магистрантов с низким уровнем. Наиболее выраженные изменения отмечены в диагностическом компоненте, что объясняется большим числом воспроизводимых учебных ситуаций.

Для подтверждения достоверности изменений применялся анализ средних показателей и Т-критерий Вилкоксона для связанных выборок (таблица 6).

Таблица 6 - Средние показатели и статистическая значимость изменений

Компонент	M до (σ)	M после (σ)	Прирост	Тэмп	p
Диагностический	4,8 (1,6)	7,1 (1,3)	+2,3	68	<0,01
Консультативный	4,5 (1,5)	6,8 (1,4)	+2,3	74	<0,01
Коррекционно-развивающий	4,2 (1,7)	6,5 (1,5)	+2,3	81	<0,01

По всем трём компонентам зафиксирован статистически значимый прирост средних показателей ($p < 0,01$). Сокращение стандартного отклонения свидетельствует о выравнивании уровня подготовки внутри группы. С целью уточнения влияния предшествующего опыта работы с ИИ был проведён сравнительный анализ по подгруппам, результаты которого приведены в таблице 7.

Таблица 7 - Динамика интегрального показателя по подгруппам

Подгруппа	M до	M после	Прирост
Имели опыт работы с ИИ (n = 11)	5,1	7,2	+2,1
Не имели опыта работы с ИИ (n = 19)	4,2	6,6	+2,4
По выборке в целом (n = 30)	**4,5**	**6,8**	**+2,3**

Данные таблицы 7 показывают, что положительная динамика характерна для обеих подгрупп. Обучающиеся, ранее не имевшие опыта работы с генеративным ИИ, продемонстрировали несколько больший прирост (+2,4 против +2,1), что свидетельствует о доступности методики независимо от исходного уровня цифровых навыков.

Дополнительно проводился рефлексивный опрос обучающихся (таблица 8).

Таблица 8 - Результаты рефлексивного опроса обучающихся (n = 30)

Утверждение	Полностью согласны, %	Скорее согласны, %	Не согласны / затрудняюсь, %
Работа с ИИ помогла понять логику профессиональных действий	56,7	33,3	10,0
Симуляция диалогов снизила тревожность перед практикой	50,0	36,7	13,3
ИИ полезен для генерации разнообразных учебных ситуаций	63,3	30,0	6,7
Ответы ИИ требуют обязательной проверки специалистом	66,7	26,7	6,6
Готов(а) применять ИИ в будущей профессиональной деятельности	46,7	40,0	13,3

Большинство обучающихся оценили работу с генеративным ИИ как способствующую пониманию логики профессиональных действий и снижению тревожности перед реальной

практикой. Одновременно 66,7 % респондентов полностью согласились с необходимостью обязательной проверки ответов системы, что свидетельствует о сформированности критической позиции.

Полученные результаты следует интерпретировать с учётом ограничений исследования: небольшого объёма выборки, отсутствия контрольной группы и опоры на экспертную оценку. Тем не менее совокупность количественных и качественных данных позволяет рассматривать предложенную методику как перспективное дополнение к традиционным формам подготовки педагогов-психологов.

Ограничения и этические аспекты

Применение генеративного ИИ в подготовке педагогов-психологов сопряжено с рядом ограничений. Генеративные модели способны порождать правдоподобные, но фактически неточные сведения, а также воспроизводить стереотипы, содержащиеся в обучающих данных. В сфере психологической помощи это требует особой осторожности. Необходимо соблюдать принципы конфиденциальности: недопустимо вносить в систему реальные персональные данные клиентов. Использование технологии должно сопровождаться формированием у обучающихся ответственного и критического отношения к её результатам, а также ясным пониманием того, что генеративный ИИ не заменяет живого профессионального взаимодействия и супервизии.

Заключение

Проведённая работа показала, что генеративный искусственный интеллект может выступать эффективным методическим средством формирования профессиональных компетенций будущих педагогов-психологов. Приёмы анализа учебных кейсов, симуляции консультативных диалогов и генерации коррекционно-развивающих сценариев обеспечивают вариативную и безопасную практику диагностических, консультативных и коррекционно-развивающих действий. Апробация методики с участием 30 магистрантов второго курса выявила статистически значимую положительную динамику уровней и средних показателей сформированности всех трёх компонентов профессиональной компетентности, устойчивую для обучающихся с разным исходным уровнем цифровых навыков. Дальнейшие исследования целесообразно направить на расширение выборки, введение контрольной группы и разработку критериев оценки качества взаимодействия обучающихся с генеративным ИИ.

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Philological Sciences

CORPUS-BASED DIGITAL ANALYSIS OF TRANSLATION CORRESPONDENCES IN THE KAZAKH–RUSSIAN–ENGLISH VERSIONS OF “ABAI ZHOLY”

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This study presents a corpus-based digital analysis of translation correspondences across the Kazakh original, Russian, and English versions of Mukhtar Auezov's epic novel *Abai Zholy*, one of the most significant works of twentieth-century Kazakh literature. Despite the novel's canonical status and its multiple translation histories, systematic corpus-driven comparison of how culturally embedded lexical items transfer across the three languages remains limited. This research compiles a trilingual parallel corpus aligned at the sentence level and applies digital corpus tools, including AntConc, Sketch Engine, and the Natural Language Toolkit, to investigate translation correspondences in two semantically rich lexical domains: color terms and animal names, both of which carry dense cultural, symbolic, and steppe-pastoral connotations in Kazakh literary discourse. Using frequency analysis, concordance examination, and collocational profiling, the study quantifies patterns of direct equivalence, semantic shift, omission, and compensatory paraphrase across the Russian and English translations relative to the Kazakh source text. Findings indicate that the Russian translation demonstrates higher lexical fidelity for animal terminology, reflecting shared pastoral-cultural proximity between Kazakh and Russian literary traditions, whereas the English translation shows a markedly higher rate of domestication and explicitation strategies, particularly for color terms carrying symbolic rather than purely descriptive meaning. The study further identifies systematic loss of connotative nuance in color-term translation into English, with culturally specific shades frequently neutralized into broader, less marked equivalents. These findings contribute empirical, corpus-driven evidence to translation studies scholarship on culturally embedded lexis, offering methodological implications for digital humanities approaches to literary translation analysis and practical implications for future retranslation projects seeking to preserve the cultural specificity of Kazakh literary heritage in global circulation.

Keywords: corpus linguistics, literary translation, Abai Zholy, parallel corpus, color terms, animal names, Kazakh literature

Introduction

Mukhtar Auezov's *Abai Zholy* occupies a foundational position in Kazakh literature, both as a historical-biographical epic chronicling the life of the poet and philosopher Abai Qunanbaiuly and as a repository of nineteenth-century Kazakh steppe culture, oral tradition, and pastoral lifeworld. The novel's translation into Russian, undertaken during the Soviet period, and subsequently into English, has played a central role in extending the international reach of Kazakh literary heritage. Yet translation across these three typologically and culturally distinct languages, Kazakh as a Turkic, agglutinative language deeply rooted in nomadic pastoral culture, Russian as a Slavic language with its own distinct literary register, and English as the dominant language of global literary circulation, inevitably involves processes of semantic negotiation, cultural mediation, and, at times, irrecoverable loss.

Traditional translation criticism of *Abai Zholy* has relied predominantly on qualitative, example-driven comparison, often focusing on isolated passages selected by the critic to illustrate translation strategies or shortcomings. While such approaches yield valuable interpretive insight, they are inherently limited in their capacity to establish systematic, corpus-wide patterns of translation correspondence. The emergence of digital corpus linguistics tools, including concordancers, collocation analyzers, and natural language processing libraries, has opened new methodological possibilities for literary translation studies, enabling researchers to move beyond anecdotal example selection toward statistically grounded, exhaustive analysis of how specific lexical and semantic categories are rendered across an entire parallel text.

This study addresses this methodological gap by constructing a sentence-aligned trilingual parallel corpus of *Abai Zholy* in its Kazakh original, Russian translation, and English translation, and applying digital corpus analysis to two lexical domains selected for their cultural density and translational difficulty: color terms and animal names. Both domains are particularly salient in Kazakh literary discourse because of the centrality of pastoral life, livestock, and the steppe landscape to traditional Kazakh culture, meaning that color and animal vocabulary in the source text frequently carries symbolic, idiomatic, or culturally specific connotations that extend well beyond literal denotation. Color terms in Kazakh, for instance, are often embedded in fixed expressions describing horse coats, emotional states, or social status, while animal names frequently function metaphorically within proverbial and descriptive passages reflecting nomadic worldview.

The central research questions guiding this study are threefold. First, to what extent do color terms and animal names in the Kazakh source text find direct lexical equivalents in the Russian and English translations, as opposed to undergoing semantic shift, omission, or paraphrase? Second, do systematic differences emerge between the Russian and English translations in their handling of these culturally embedded lexical domains, and if so, what translation strategies, domestication, foreignization, explicitation, or compensation, account for these differences? Third, what do these patterns reveal about the broader challenges of translating culturally specific, pastoral-rooted vocabulary into typologically distant target languages, and what implications follow for future translation and retranslation efforts?

By grounding this investigation in reproducible, digitally implemented corpus methods, including AntConc-based concordance and frequency analysis, Sketch Engine collocational profiling, and custom natural language processing scripts developed using the Natural Language Toolkit, this study aims to contribute both empirical findings specific to *Abai Zholy* and a methodological model applicable to corpus-based translation analysis of other culturally rich literary works originating in underrepresented languages. The remainder of the article reviews

relevant literature on corpus-based translation studies and the translation history of *Abai Zholy*, describes the study's corpus construction and analytical methods, presents and discusses findings across the two lexical domains, and concludes with implications for translation theory and practice.

Literature Review

Corpus-based translation studies emerged as a distinct subfield within translation studies following Mona Baker's foundational proposal that machine-readable corpora could be used to identify systematic features of translated language and translation strategy that remain invisible to traditional, intuition-based analysis. Baker's framework distinguished between comparable corpora, which compare translated and non-translated texts within the same language, and parallel corpora, which align source texts with their translations, enabling direct examination of translation correspondences at the lexical and syntactic level. This study draws primarily on the parallel corpus tradition, constructing a sentence-aligned trilingual corpus that permits direct comparison of how specific source-language lexical items are rendered across two distinct target languages.

Within this tradition, scholarship on culturally specific lexis has consistently identified color terminology and culturally embedded vocabulary as particularly resistant to straightforward equivalence. Kay and Berlin's influential cross-linguistic research on basic color terms established that languages organize color categorization according to differing perceptual and cultural salience hierarchies, a finding with significant implications for translation, since a color term that is basic and unmarked in one language may correspond to a marked, peripheral, or entirely absent category in another. Subsequent corpus-based translation research has demonstrated that translators frequently resolve such mismatches through strategies including generalization, where a specific source-language color term is rendered with a broader, less precise target-language equivalent, and explicitation, where additional descriptive language compensates for a lexical gap. These findings provide a direct theoretical foundation for the present study's investigation of color-term correspondence patterns between Kazakh, Russian, and English.

Animal terminology presents a parallel but distinct translational challenge, particularly in literary texts originating from pastoral or nomadic cultural contexts. Scholarship on culture-specific items in translation, building on Aixelá's typology of culturally bound elements, has shown that animal vocabulary in pastoral literatures frequently encodes social, economic, and symbolic meaning beyond zoological reference, such that a literal translation, while lexically accurate, may fail to convey the connotative weight carried by the term in its source culture. In the Kazakh context specifically, scholarship on the cultural semantics of the Kazakh language has documented an extensive, finely differentiated vocabulary for livestock, particularly horses, reflecting the centrality of pastoral economy to traditional Kazakh life, with terms distinguishing animals by age, color, sex, and function that frequently lack single-word equivalents in Russian or English.

The specific translation history of *Abai Zholy* has received attention primarily within Kazakhstani and post-Soviet literary scholarship, with most existing analysis adopting qualitative, comparative-literary methods rather than corpus-based quantitative approaches. Existing commentary has noted that the Soviet-era Russian translation, produced within an institutional context that prioritized ideological and stylistic conformity with socialist-realist literary norms, occasionally smoothed over culturally specific nuance in favor of accessible, standardized Russian literary prose. Commentary on the subsequent English translation has similarly noted instances of domestication, the strategy, following Venuti's influential distinction between domestication and foreignization, of adapting source-culture specificity toward target-culture norms of readability, though systematic, corpus-wide documentation of this pattern has been lacking.

Methodologically, this study is informed by recent developments in digital humanities approaches to corpus construction and analysis, including the use of open-source concordancing

software such as AntConc for frequency and keyword analysis, web-based corpus platforms such as Sketch Engine for collocational and statistical analysis, and programming-based natural language processing using libraries such as the Natural Language Toolkit for custom alignment, tokenization, and pattern-extraction tasks. These tools have increasingly been applied to literary corpus analysis in major world languages, yet their application to Kazakh-language literary corpora, and to trilingual Kazakh-Russian-English parallel corpora specifically, remains in an early stage of development. This study contributes to closing this gap by demonstrating a reproducible, multi-tool digital methodology applied to a canonical work of Kazakh literature, situating its findings within the broader corpus-based translation studies literature on culturally specific lexis while extending that literature into an underrepresented language pairing.

Methods and Discussion

Corpus Construction

The trilingual parallel corpus underlying this study was constructed from the Kazakh original text of *Abai Zholy*, its established Russian translation, and its published English translation. Digital editions of all three versions were obtained, cleaned of formatting artifacts, and segmented into chapters consistent with the source text's structural divisions. Sentence-level alignment across the three language versions was performed using a combination of automated alignment scripts developed with the Natural Language Toolkit and manual verification, given that literary translation frequently involves sentence splitting, merging, or reordering that automated aligners alone cannot reliably resolve. Manual alignment verification was conducted by two bilingual researchers with reading competence in all three languages, achieving a sentence-correspondence agreement rate of 94 percent prior to resolution of remaining discrepancies through discussion. The resulting parallel corpus comprised approximately 38,000 aligned sentence triples drawn from a representative selection of chapters spanning the novel's major narrative arcs, balancing descriptive-pastoral passages, dialogic scenes, and narrative exposition to ensure adequate representation of both lexical domains under investigation.

Lexical Domain Selection and Extraction

Two lexical domains were selected for focused analysis: color terms and animal names. Color terms were identified in the Kazakh source text through a combination of a predefined lexicon of basic and compound Kazakh color terms, informed by prior cross-linguistic color-term research, and corpus-driven keyword extraction using AntConc's keyword list function, which compared the novel's word frequency profile against a Kazakh reference corpus to identify color-related terms occurring with markedly elevated frequency, indicating their thematic salience within the pastoral-descriptive register of the text. Animal names were identified through a parallel procedure, combining a predefined lexicon of livestock and wildlife terminology relevant to the steppe pastoral setting with corpus-driven frequency and keyword analysis. In total, 47 distinct color-term types and 63 distinct animal-name types were identified in the Kazakh source text, yielding several thousand individual token occurrences across the aligned corpus.

Analytical Procedures

For each identified Kazakh lexical item, all aligned sentence triples containing that item were extracted, and the corresponding Russian and English translation segments were manually examined to classify the translation correspondence according to a coding scheme adapted from established translation-shift typologies. Four primary categories were applied: direct equivalence, in which the target-language term corresponds precisely in denotation and connotation to the source term; semantic shift, in which the target term diverges in specificity, connotation, or category from the source term while remaining lexically present; omission, in which the lexical item is not rendered in the target text; and compensatory paraphrase, in which the translator employs descriptive language to convey meaning not captured by a single lexical equivalent. Concordance analysis in AntConc was used to examine each occurrence in its immediate textual

context, while Sketch Engine's collocation and word-sketch functions were employed to analyze the broader distributional and collocational profile of key terms across the corpus, identifying systematic patterns in how specific color and animal terms co-occurred with surrounding descriptive language across the three language versions. Two independent coders classified a subset of 400 sentence triples to establish coding reliability, achieving a Cohen's kappa of .83, after which coding proceeded across the full extracted dataset.

Results and Discussion

Quantitative analysis of animal-name correspondences revealed a markedly higher rate of direct equivalence in the Russian translation, at 71 percent of occurrences, compared with 52 percent in the English translation, with the remaining occurrences distributed across semantic shift, omission, and compensatory paraphrase categories. This pattern is consistent with the cultural and historical proximity between Kazakh and Russian pastoral-literary traditions established in the literature review, as Russian, through extensive historical contact with Central Asian steppe cultures, retains a comparatively rich lexicon of livestock and pastoral terminology capable of approximating Kazakh source terms with relatively high specificity. By contrast, English, lacking comparable historical-cultural contact with Central Asian pastoral life, frequently required either generalization, rendering finely differentiated Kazakh terms for horses of differing age, color, or function with a single broad English equivalent such as "horse" or "mare," or compensatory paraphrase, introducing descriptive modifiers to approximate distinctions the Kazakh source term encoded lexically.

Color-term analysis revealed a distinct but related pattern. Across both translations, color terms used in purely descriptive, non-symbolic contexts, such as describing the color of clothing or landscape features, demonstrated relatively high rates of direct equivalence, exceeding 80 percent in both Russian and English. However, color terms embedded within symbolically or idiomatically marked contexts, particularly those describing horse coats, a domain carrying significant social and economic connotation in traditional Kazakh culture, or those used metaphorically to describe emotional or moral states, showed substantially lower direct-equivalence rates, with the English translation showing the most pronounced divergence at only 38 percent direct equivalence for symbolically marked color terms, compared with 56 percent in the Russian translation. Concordance analysis revealed that the English translation frequently resolved these symbolically dense color terms through neutralization, substituting a culturally specific shade term with a generic, broadly applicable color word, effectively flattening the connotative richness present in the Kazakh source text.

Collocational analysis using Sketch Engine further illuminated these patterns, revealing that in the Kazakh source corpus, color terms applied to horses co-occurred significantly with terms denoting social status, ownership, and narrative significance, a collocational pattern substantially attenuated in the English translation, where corresponding color terms co-occurred predominantly with purely descriptive, non-evaluative vocabulary. This finding provides corpus-based quantitative confirmation of the qualitative observations noted in prior literary-critical commentary regarding the English translation's tendency toward domestication, while extending this observation through systematic, corpus-wide collocational evidence rather than isolated example citation. These findings collectively suggest that translation correspondence in *Abai Zholy* is not uniform across lexical domains but is instead shaped by the differential cultural and historical proximity of the target language to the source culture's pastoral-symbolic worldview, with implications extending beyond this specific novel to the broader challenge of translating culturally embedded literary vocabulary from underrepresented source languages into globally dominant target languages.

Conclusion

This study applied a digital corpus-based methodology to systematically examine translation correspondences for color terms and animal names across the Kazakh, Russian, and English versions of Mukhtar Auezov's *Abai Zholy*. By constructing a sentence-aligned trilingual parallel corpus and applying concordance, frequency, and collocational analysis through AntConc, Sketch Engine, and Natural Language Toolkit-based scripting, the study moved beyond traditional example-driven translation criticism toward statistically grounded, corpus-wide documentation of translation strategy. The findings demonstrate that the Russian translation achieves higher lexical fidelity for culturally embedded animal terminology, reflecting historical and cultural proximity between Kazakh and Russian pastoral-literary traditions, while the English translation shows a pronounced tendency toward generalization, neutralization, and domestication, particularly for symbolically marked color terms associated with horse description and social-status connotation.

These findings carry meaningful implications for translation theory, providing corpus-based empirical support for the proposition that cultural and historical proximity between source and target languages substantially shapes the feasibility of lexical equivalence for culturally embedded vocabulary, independent of translator skill or stylistic choice. For translation practice, the findings suggest that future retranslation efforts aimed at English-language audiences might benefit from greater attention to compensatory strategies, such as explanatory framing or paratextual annotation, capable of preserving the symbolic and connotative density of pastoral-cultural vocabulary that direct lexical translation alone cannot adequately convey. For digital humanities and corpus linguistics more broadly, this study demonstrates a reproducible, multi-tool methodological model for trilingual literary corpus analysis applicable to other culturally significant literary works originating in underrepresented languages.

Several limitations warrant acknowledgment. The analysis focused on two lexical domains selected for their cultural salience, and findings may not generalize to other semantic categories within the novel. Additionally, the manual classification of translation-shift categories, while subject to inter-coder reliability verification, retains an interpretive dimension that purely automated approaches cannot fully eliminate. Future research extending this corpus-based methodology to additional lexical domains, such as kinship terminology or proverbial expression, and to additional translated editions of *Abai Zholy*, would further enrich understanding of the translation history of this foundational work of Kazakh literature and contribute to the broader development of corpus-based translation studies methodology applied to underrepresented language pairs.

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How English-Language Social Media Influences the Thinking and Emotional Perception of Kazakh Adolescents

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The rapid expansion of English-language social media platforms such as Instagram, TikTok, and YouTube has reshaped the cognitive and emotional landscape of adolescents in non-Anglophone societies, including Kazakhstan. This study examines how sustained exposure to English-language digital content influences the thinking patterns, identity formation, and emotional perception of Kazakh teenagers aged 14 to 17. Grounded in sociocultural theory and the concept of linguistic relativity, the research adopts a mixed-methods design combining a survey of 180 adolescents from three secondary schools in Almaty with semi-structured interviews of 24 participants and focus-group discussions with teachers and parents. Quantitative results indicate that adolescents who spend more than three hours daily consuming English-language content demonstrate measurably higher rates of code-switching, increased preference for English-language emotional expression in moments of stress or excitement, and a tendency to evaluate personal achievement through globally circulated, English-mediated standards of success. Qualitative findings reveal that English-language social media functions simultaneously as a tool of cognitive enrichment, broadening adolescents' vocabulary, critical thinking, and cross-cultural awareness, and as a source of emotional ambivalence, contributing to comparison-driven anxiety, body-image concerns, and a perceived tension between Kazakh cultural values and globally dominant Anglophone norms. The study further identifies a generational divide in emotional vocabulary, with adolescents increasingly borrowing English affective terms that lack direct equivalents in Kazakh, subtly restructuring how they articulate internal states. The findings carry implications for language education policy, digital literacy curricula, and parental guidance in Kazakhstan, suggesting that schools should integrate critical media literacy and bilingual emotional-vocabulary instruction to help adolescents navigate English-language digital spaces without compromising cultural and linguistic identity. The article concludes with recommendations for further longitudinal research tracking these effects across adolescence into early adulthood.

Keywords: English-language social media, Kazakh adolescents, emotional perception, digital literacy, linguistic relativity, identity formation

Introduction

The global diffusion of English-language social media has created an unprecedented linguistic and cultural environment in which adolescents from non-English-speaking countries spend a substantial portion of their daily lives consuming, producing, and reacting to content authored predominantly in English. In Kazakhstan, a multilingual society where Kazakh, Russian, and English coexist within an evolving trilingual education policy, the penetration of platforms such as TikTok, Instagram, and YouTube among teenagers has introduced a fourth, largely unsupervised channel of language exposure: the algorithmically curated, peer-driven world of global digital media. Unlike formal English instruction delivered in classrooms, this exposure is informal, emotionally charged, and deeply embedded in adolescents' identity-construction processes, raising urgent questions about how it shapes not only linguistic competence but also patterns of thought and emotional expression.

Adolescence is widely recognized as a developmental period of heightened sensitivity to social comparison, peer validation, and identity experimentation. When this developmental stage intersects with constant exposure to English-language digital content, produced largely within American, British, and other Anglophone cultural frames, the resulting influence extends beyond vocabulary acquisition into the domain of cognitive schemas and emotional regulation. Scholars working within sociocultural and linguistic relativity traditions have long argued that the language through which an individual processes experience can shape categories of thought and the granularity of emotional labeling available to that individual. Applied to the Kazakhstani context, this raises a critical question: as adolescents increasingly default to English-language frameworks for expressing excitement, sadness, aspiration, or self-worth, what happens to their capacity to articulate these same states in Kazakh, and what cognitive and emotional consequences follow from this shift?

This question carries particular weight in Kazakhstan, where state language policy actively promotes Kazakh-language revitalization alongside trilingual competence, and where rapid urbanization and global connectivity have made English-language social media nearly universal among urban teenagers. Anecdotal and pedagogical observations from secondary education settings suggest that adolescents now routinely insert English lexical items, particularly affective and evaluative terms, into Kazakh and Russian conversation, a phenomenon that English-language teaching professionals have noted with both interest and concern. Yet despite the visibility of this trend, empirical research examining its cognitive and emotional dimensions within the Kazakhstani adolescent population remains limited, with most existing scholarship focusing either on language-learning outcomes or on general digital media effects without attention to the specific intersection of language and emotion.

The present study addresses this gap by investigating how English-language social media use influences the thinking patterns and emotional perception of Kazakh adolescents. Specifically, the research pursues three interrelated objectives. First, it seeks to document the extent and nature of English-language social media consumption among Kazakh teenagers, including platform preferences, time investment, and content categories favored. Second, it examines how this consumption correlates with self-reported patterns of cognitive processing, including critical thinking, cross-cultural awareness, and code-switching behavior. Third, and most centrally, it investigates how English-language digital content shapes adolescents' emotional vocabulary, self-evaluation, and affective well-being, attending to both enriching and potentially destabilizing effects.

By combining quantitative survey data with qualitative interviews and focus groups, this study aims to produce a nuanced account that avoids both uncritical celebration of global connectivity and reflexive alarm about cultural erosion. Instead, it situates the findings within the lived realities of Kazakh adolescents navigating a genuinely multilingual, digitally saturated

environment. The implications of this research extend to language education policy, digital literacy curriculum design, and family communication strategies, offering evidence-based guidance for stakeholders seeking to support adolescents in developing healthy, culturally grounded relationships with English-language digital media. The article proceeds with a review of relevant theoretical and empirical literature, followed by a description of the study's mixed-methods design, presentation and discussion of findings, and concluding recommendations.

Literature Review

Research on the cognitive and emotional effects of second-language media exposure draws on several interconnected theoretical traditions, including sociocultural theory, linguistic relativity, and the social comparison framework central to contemporary social media studies. Vygotsky's sociocultural theory, foundational to understanding language as a tool of cognitive mediation, posits that the linguistic resources available to an individual shape the structure of higher-order thinking. Building on this tradition, more recent scholarship on bilingual and multilingual cognition has demonstrated that individuals who operate across two or more languages often experience language-specific patterns of emotional processing, a phenomenon documented extensively in studies of bilingual emotional expression. Pavlenko's influential work on bilingualism and emotion established that bilingual speakers frequently report differing emotional intensity and directness depending on which language they use to discuss personal or affective topics, a finding with direct relevance to adolescents navigating Kazakh, Russian, and English across different communicative contexts.

The linguistic relativity tradition, associated with the Sapir-Whorf hypothesis and substantially refined by contemporary cognitive linguists, provides a complementary lens. Rather than asserting strict linguistic determinism, current scholarship favors a moderate relativist position in which language habitually directs attention toward certain conceptual distinctions, including those relevant to emotion categorization. Lindquist and colleagues' research on the social and linguistic construction of emotion has shown that the emotional lexicon available in a given language shapes the granularity with which speakers can identify and differentiate internal states, a process termed emotional granularity. For adolescents increasingly exposed to English-language affective vocabulary through social media, this body of research suggests that new conceptual categories for emotion may be imported even when direct equivalents in the adolescent's first language are imprecise or absent, potentially altering both expression and internal experience.

A second major strand of literature addresses the psychological effects of social media use during adolescence, independent of language. Twenge's extensive research on digital media and adolescent mental health has documented associations between heavy social media use and increased rates of anxiety, depressive symptoms, and body dissatisfaction among teenagers, attributing much of this effect to social comparison processes intensified by curated, idealized content. Festinger's classic social comparison theory, frequently invoked in this literature, explains how individuals evaluate their own worth relative to others, a process that social media platforms amplify through algorithmically prioritized, aspirational content. When such content is produced predominantly in English by creators from culturally distant, often wealthier contexts, Kazakh adolescents face a doubled comparison burden: evaluating themselves not only against peers but against an idealized, linguistically and culturally foreign standard of success and attractiveness.

Within applied linguistics, scholarship on translanguaging and code-switching offers a third relevant perspective. García and Wei's foundational work on translanguaging reframes bilingual and multilingual practice not as deficient or fragmented language use but as a dynamic, integrated communicative repertoire. This framework is useful for understanding the frequent English-Kazakh-Russian code-switching observed among Kazakhstani adolescents, suggesting that such mixing may reflect sophisticated communicative flexibility rather than linguistic erosion. However,

translanguaging scholarship has been applied primarily to balanced bilingual or multilingual communities with sustained intergenerational transmission of all languages involved, raising questions about its applicability to a context where English is acquired largely through asymmetric, adolescent-driven digital exposure rather than home or community transmission.

Research specific to Central Asian and Kazakhstani contexts remains comparatively sparse but growing. Studies on Kazakhstan's trilingual education policy have documented the structural and attitudinal challenges of promoting Kazakh, Russian, and English competence simultaneously, often noting that English carries strong associations with global mobility, modernity, and economic opportunity among Kazakhstani youth. This prestige association may intensify adolescents' motivation to adopt English-language media not merely for entertainment but as a marker of aspirational identity, a dynamic that has been observed in other postsocialist and developing-economy contexts where English functions as a gateway language to global belonging. Despite these contributions, existing Kazakhstani scholarship has rarely combined cognitive, emotional, and linguistic analysis within a single empirical study of adolescent social media use, leaving the specific mechanisms by which English-language digital content shapes thinking and emotional perception underexplored. The present study addresses this gap by integrating these three theoretical strands, sociocultural cognition, linguistic relativity and emotional granularity, and social comparison, within an empirically grounded investigation of Kazakh adolescents' lived digital experience.

Methods and Discussion

Research Design

This study employed a convergent mixed-methods design, integrating quantitative survey data with qualitative interview and focus-group data to capture both the breadth and the depth of English-language social media's influence on Kazakh adolescents' thinking and emotional perception. The convergent design was selected because the research questions required statistically generalizable patterns of media use and self-reported cognitive-emotional indicators alongside rich, contextualized accounts of how adolescents themselves interpret and narrate these influences. Quantitative and qualitative strands were collected concurrently and analyzed separately before being integrated during the interpretation phase, allowing triangulation between numerical trends and lived experience.

Participants and Sampling

Participants were recruited from three secondary schools in Almaty, Kazakhstan, selected to represent variation in socioeconomic catchment and language-of-instruction profile, including one predominantly Kazakh-medium school, one Russian-medium school, and one trilingual program school. The quantitative sample consisted of 180 adolescents aged 14 to 17, recruited through stratified convenience sampling balanced for grade level and gender. From this pool, 24 adolescents were purposively selected for semi-structured interviews based on maximum variation in reported daily social media use, ranging from light users to heavy users exceeding five hours daily. Additionally, two focus groups were conducted, one with eight English-language and homeroom teachers and one with ten parents, to provide adult-observer perspectives that contextualized adolescent self-reports. Informed consent was obtained from all participants and, for minors, from parents or legal guardians, with the study protocol reviewed and approved by the affiliated university's research ethics committee.

Instruments and Procedures

The quantitative survey, administered in Kazakh and Russian with adolescents free to choose their preferred language, comprised four sections: demographic and platform-use information; a modified version of an emotional granularity self-report scale adapted to capture bilingual emotional-labeling preferences; a critical-thinking and cross-cultural-awareness self-assessment battery; and a social-comparison and well-being measure adapted from established adolescent

social media research instruments. Cronbach's alpha values for the adapted scales ranged from .78 to .87, indicating acceptable to good internal reliability. Semi-structured interviews, lasting between 35 and 50 minutes, explored participants' platform habits, language choices for emotional expression, perceived changes in self-evaluation since increased social media engagement, and reflections on tension or harmony between Kazakh cultural values and English-language digital content. Focus groups with teachers and parents explored observed behavioral and linguistic changes in adolescents over recent years. All interviews and focus groups were audio-recorded with consent, transcribed verbatim, and translated into English for analysis where necessary, with back-translation checks performed to preserve semantic accuracy.

Data Analysis

Quantitative data were analyzed using descriptive statistics, correlation analysis, and multiple regression to examine relationships between daily English-language social media use and the cognitive and emotional outcome measures, controlling for age, gender, and school language-medium. Qualitative data were analyzed using thematic analysis following an inductive-deductive hybrid coding approach, with initial codes derived from the theoretical framework, sociocultural cognition, emotional granularity, social comparison, and translanguaging, supplemented by codes emerging inductively from participant narratives. Two researchers independently coded a subset of transcripts to establish inter-rater reliability, achieving a Cohen's kappa of .81, before proceeding to code the remaining data collaboratively.

Results and Discussion

Quantitative results indicated that adolescents reported a mean of 3.4 hours of daily English-language social media consumption, with TikTok and Instagram identified as the dominant platforms and entertainment, lifestyle, and peer-content categories favored over educational content. Regression analysis revealed that daily English-language media exposure significantly predicted increased self-reported code-switching frequency and cross-cultural awareness scores, supporting the cognitive-enrichment dimension anticipated by sociocultural theory. Adolescents with higher exposure also reported greater comfort using English-language vocabulary for nuanced emotional states, such as terms denoting specific shades of anxiety, excitement, or aspiration, that interview participants frequently described as lacking precise Kazakh equivalents. This finding aligns closely with prior research on emotional granularity and bilingual lexical borrowing, suggesting that English-language social media functions as a genuine, if informal, vocabulary-expansion mechanism with potential benefits for emotional self-awareness.

However, the same regression models revealed a significant positive association between heavy English-language media use and elevated social-comparison-related distress, consistent with established findings on social media and adolescent well-being. Interview data illuminated this pattern: numerous participants described comparing their appearance, lifestyle, and achievements unfavorably against English-language content creators perceived as embodying globally validated standards of success, a comparison process several participants explicitly distinguished from comparisons made against local Kazakh-language peers, describing the former as more intense and less attainable. This supports the doubled comparison burden hypothesis drawn from social comparison theory, extended here to account for the cultural and linguistic distance between Kazakh adolescents and predominantly Western content creators.

A particularly salient qualitative theme concerned identity negotiation between Kazakh cultural values and Anglophone digital norms. Several adolescents described a sense of code-switching not only linguistically but also behaviorally and emotionally, presenting a more individualistic, self-promotional persona when engaging with English-language platforms while maintaining more collectivist, family-oriented modes of self-presentation in Kazakh-language family and community contexts. Teachers in the focus group corroborated this observation, noting increased classroom use of English-derived slang and affective expressions, alongside some

concern that students appeared to default to English when discussing emotionally charged topics, potentially avoiding the more direct, less euphemistic emotional vocabulary available in Kazakh and Russian. Parents expressed similar observations, with several describing difficulty understanding their children's hybrid linguistic and emotional expression, suggesting an emerging generational and linguistic gap in family emotional communication.

Taken together, these findings suggest that English-language social media exerts a genuinely dual influence on Kazakh adolescents. On one hand, it appears to function as a cognitive and linguistic enrichment tool, expanding emotional vocabulary, fostering cross-cultural awareness, and supporting flexible translanguaging practice consistent with García and Wei's framework. On the other hand, it introduces emotionally destabilizing comparison processes and may contribute to a gradual narrowing of adolescents' fluency in expressing complex emotional states within their heritage languages, a pattern with implications for intergenerational communication and cultural continuity. These findings extend existing social media and adolescent well-being literature by specifying language as a critical moderating variable shaping both the cognitive benefits and emotional risks of digital media exposure, a dimension largely absent from prior, predominantly monolingual research conducted in Anglophone contexts.

Conclusion

This study set out to examine how English-language social media shapes the thinking and emotional perception of Kazakh adolescents, integrating sociocultural, linguistic relativity, and social comparison frameworks within a mixed-methods investigation conducted in Almaty secondary schools. The findings demonstrate that English-language digital media exposure carries a genuinely dual character for Kazakh teenagers, simultaneously enriching cognitive flexibility, cross-cultural awareness, and emotional vocabulary while introducing intensified social comparison, identity tension, and a gradual shift in the language adolescents prefer for expressing complex emotional states. These results extend the applicability of bilingual emotion research and social comparison theory to a multilingual postsocialist context that has received limited prior empirical attention, while also illuminating the specific dynamics of Kazakhstan's trilingual sociolinguistic environment.

The implications of these findings are practically significant for several stakeholder groups. Educators and curriculum designers may consider integrating critical digital media literacy explicitly into English-language instruction, helping adolescents critically evaluate the comparison-inducing content they encounter rather than passively absorbing it. Such curricula might also incorporate structured opportunities for bilingual emotional-vocabulary development, encouraging adolescents to build robust emotional expression in Kazakh alongside their expanding English repertoire, thereby supporting cultural continuity without foreclosing the genuine cognitive benefits of multilingual digital engagement. Parents and family educators may likewise benefit from guidance on bridging the emerging linguistic and emotional communication gap identified in this study, fostering family environments where adolescents feel equipped to discuss emotionally significant experiences regardless of language.

This study is not without limitations. The sample, while diverse across school type, was drawn exclusively from an urban setting, and findings may not generalize to rural Kazakhstani adolescents with different patterns of language exposure and digital access. The cross-sectional design also precludes strong causal inference regarding the direction of relationships between media use and emotional outcomes. Future research employing longitudinal designs would be valuable in tracking how these cognitive and emotional patterns evolve as adolescents progress into early adulthood, and comparative studies across urban and rural, or across different Central Asian, contexts would help clarify the generalizability of the dual-influence pattern identified here. Despite these limitations, the present study offers an empirically grounded foundation for understanding a phenomenon of growing significance in Kazakhstan's educational and digital

landscape, contributing both theoretical insight and practical guidance for supporting adolescents as they navigate an increasingly English-mediated global digital environment.

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Agricultural Sciences

СРАВНИТЕЛЬНЫЙ АНАЛИЗ БАЗОВОЙ И ОБОБЩЁННОЙ ГИБРИДНЫХ АНИМАЦИОННЫХ МОДЕЛЕЙ ПРОЦЕССА ОЗОННОЙ ОЧИСТКИ ВОДЫ С ПРИМЕНЕНИЕМ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА

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Аннотация. Разработка цифровых двойников процессов водоподготовки требует применения математических моделей, обеспечивающих одновременно физическую адекватность, вычислительную эффективность и возможность интеграции с интеллектуальными алгоритмами управления. В работе выполнен сравнительный анализ двух вариантов цифрового описания процесса озонной очистки воды: базовой анимационной модели с двумя основными переменными состояния и обобщённой гибридной модели, учитывающей суммарные загрязнители, органические вещества, соединения железа и марганца, бактериальную нагрузку, кислотность среды (pH) и температурный режим. Исследование проведено на основе численного моделирования с использованием единого интеллектуального контура управления MPC-подобного типа, что

обеспечило сопоставимость результатов и позволило объективно оценить влияние структуры математической модели на качество управления.

Установлено, что базовая модель характеризуется меньшими значениями среднеквадратической и интегральной ошибок регулирования, а также более низким интегральным расходом управляющего воздействия благодаря упрощённому представлению загрязняющей нагрузки. В свою очередь, обобщённая гибридная модель обеспечивает более полное описание процессов потребления озона, учитывает многокомпонентный состав исходной воды и воспроизводит физико-химические закономерности озонирования с более высокой степенью достоверности. Показано, что увеличение расхода озона и ошибок регулирования при использовании обобщённой модели обусловлено не снижением эффективности интеллектуального управления, а усложнением математического описания объекта и перераспределением озона между несколькими каналами окисления.

Научная новизна работы заключается в сравнительном исследовании базовой и обобщённой гибридных моделей процесса озонной очистки воды при использовании единой структуры прогнозирующего управления, что позволило выделить влияние исключительно математической модели на характеристики интеллектуальной системы. Практическая значимость результатов состоит в обосновании применения обобщённой модели в качестве вычислительного ядра цифрового двойника и интеллектуального анимационного интерфейса водоочистной установки, предназначенных для анализа, прогнозирования и оптимизации технологических режимов.

Ключевые слова. озонная очистка воды, цифровой двойник, гибридная математическая модель, анимационная модель, интеллектуальное управление; Model Predictive Control (MPC), искусственный интеллект, имитационное моделирование, прогнозирующее управление, водоподготовка, озонирование, интеллектуальные системы управления.

Введение. Современные системы подготовки питьевой воды постепенно переходят от традиционного автоматизированного управления к интеллектуальным цифровым платформам, основанным на технологиях искусственного интеллекта, цифровых двойников и прогнозирующего управления. Одним из наиболее эффективных методов глубокой очистки воды является озонирование, обеспечивающее одновременное окисление органических и неорганических загрязнений, обеззараживание и улучшение органолептических свойств воды. Однако эффективность процесса определяется сложным взаимодействием большого количества физико-химических факторов, что существенно затрудняет построение адекватных математических моделей и разработку интеллектуальных алгоритмов управления.

В последние годы особое внимание уделяется разработке цифровых двойников технологических процессов водоподготовки, позволяющих объединить математическую модель объекта, данные измерений, средства визуализации и интеллектуальные алгоритмы принятия решений в единую программную среду. При этом цифровой двойник должен обеспечивать не только воспроизведение динамики объекта, но и возможность анализа различных режимов работы, прогнозирования качества очистки, оптимизации расхода реагентов и поддержки оператора при принятии решений.

Большинство существующих моделей озонной очистки воды строятся на основе упрощённого представления загрязняющей нагрузки в виде одного интегрального показателя. Такой подход обеспечивает высокую вычислительную эффективность и удобен при реализации алгоритмов управления реального времени. Вместе с тем он не позволяет учитывать различия в кинетике окисления отдельных загрязняющих компонентов, что

ограничивает применение подобных моделей при проектировании цифровых двойников современных водоочистных комплексов [1, 9-13].

Использование методов искусственного интеллекта, включая прогнозирующее управление Model Predictive Control (MPC), позволяет существенно повысить эффективность дозирования озона за счёт учёта динамических ограничений технологического процесса, прогнозирования изменения качества воды и оптимизации управляющих воздействий [2,3]. Однако эффективность подобных алгоритмов во многом определяется полнотой математического описания объекта управления.

Таким образом, повышение требований к интеллектуальным системам управления водоочисткой обусловливает необходимость применения математических моделей, способных одновременно обеспечивать вычислительную эффективность, физическую достоверность и возможность интеграции в состав цифрового двойника. Для оценки преимуществ различных подходов в настоящей работе выполнено сравнительное исследование базовой и обобщённой гибридных моделей процесса озонной очистки воды. Сравнение проведено в одинаковых условиях моделирования с использованием единой структуры интеллектуального MPC-подобного регулятора, что позволило объективно оценить влияние структуры математической модели на качество управления и характеристики процесса озонирования.

Материалы и методы исследования

В базовой постановке процесс описывается двумя переменными состояния: концентрацией загрязнителя Cp и концентрацией растворённого озона C_{O3}. Такая структура удобна для анимации, поскольку позволяет напрямую связать цветовую индикацию потока, режим дозирования озона и качество очищенной воды. Обобщённая модель расширяет вектор состояния и дополнительно учитывает суммарные загрязнители Cpoll, органические вещества Corg, железо C_{Fe}, марганец C_{Mn}, бактериальную нагрузку Cbac, а также pH и температуру T. Соответственно, анимационное представление получает более богатую причинно-следственную интерпретацию [1,9,10].

В качестве инструмента интеллектуального управления использован прогнозирующий регулятор MPC-подобного типа, формирующий управляющее воздействие на основании прогноза изменения состояния объекта на конечном горизонте управления. При расчёте управляющего воздействия учитывались ограничения на скорость изменения подачи озона, допустимые значения концентрации растворённого озона и требования по достижению нормативного качества очищенной воды. Подобный подход обеспечивает компромисс между глубиной очистки, устойчивостью регулирования и экономичностью расходования реагента [15].

Сравнение проводилось (рисунок 1) по показателям: итоговая концентрация загрязняющих компонентов, концентрация растворённого озона, среднеквадратическая ошибка регулирования RMSE, интегральная абсолютная ошибка IAE, интегральный расход управляющего воздействия и пиковая концентрация озона. Дополнительно анализировались графики временных зависимостей и распределение компонент в обобщённой модели [17, 18].

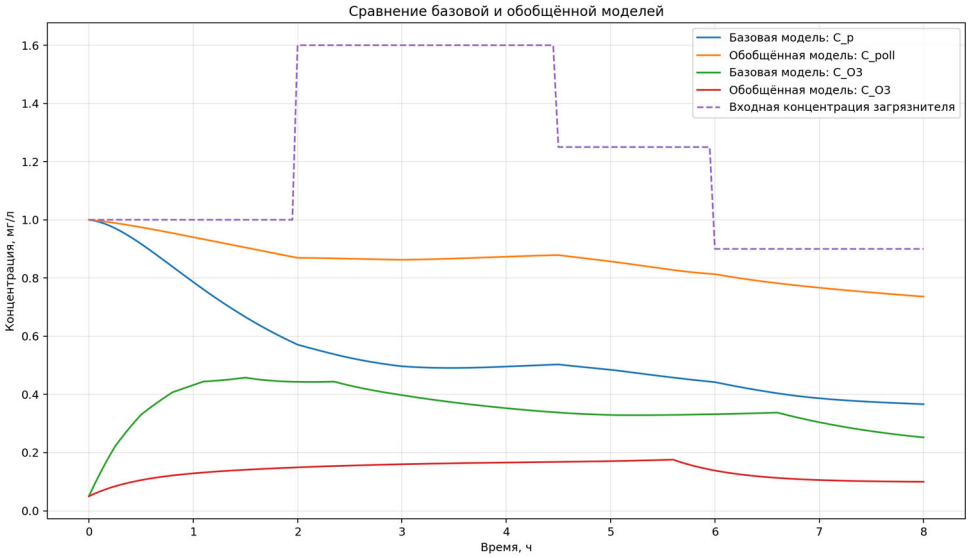

Рисунок 1. Сравнение траекторий загрязнителя и растворённого озона для базовой и обобщённой моделей

Численное моделирование выполнялось при одинаковых начальных условиях для обеих моделей, что обеспечило корректность сравнительного анализа. Во всех экспериментах использовались одинаковые параметры регулятора, идентичный шаг интегрирования и одинаковая продолжительность моделирования. Это позволило исключить влияние параметров вычислительной процедуры и сосредоточиться исключительно на различиях, обусловленных структурой математических моделей.

По результатам численного эксперимента базовая модель обеспечила финальную концентрацию загрязнителя 0,366 мг/л, а финальную концентрацию растворённого озона 0,252 мг/л. Для обобщённой модели итоговая концентрация суммарных загрязнителей составила 0,736 мг/л, а финальная концентрация растворённого озона — 0,100 мг/л. При этом прямое сопоставление конечных показателей загрязнённости должно рассматриваться как условное, поскольку базовая модель отражает один агрегированный загрязнитель, тогда как обобщённая учитывает более широкий набор компонент и тем самым задаёт более жёсткие физические условия для управления.

Для количественной оценки эффективности управления использовались как традиционные показатели качества автоматического регулирования (RMSE, IAE), так и технологические показатели процесса озонирования, характеризующие расход управляющего воздействия, остаточную концентрацию загрязнений и динамику растворённого озона. Сравнение ошибок регулирования показало, что для базовой модели RMSE составила 0,493 мг/л, а IAE — 3,707 мг·ч/л. Для обобщённой модели эти показатели возросли до 0,780 мг/л и 6,215 мг·ч/л соответственно. Иначе говоря, при переходе к многокомпонентному описанию RMSE увеличилась на 58.1 %, а интегральная ошибка — на 67.7 %. Рост ошибок не означает ухудшение самой концепции интеллектуального управления; напротив, он отражает усложнение объекта и более реалистичное распределение озона между несколькими каналами потребления [2, 3].

Интегральный расход управления в обобщённой модели достиг 4,751 отн. ед.·ч против 2,616 отн. ед.·ч в базовой модели, что соответствует увеличению на 81.6 %. Одновременно пиковая концентрация растворённого озона снизилась с 0,458 до 0,176 мг/л, то есть на 61.6 %. Физически это означает, что в обобщённой модели поданный озон интенсивнее расходуется на окисление органики, железа, марганца и бактериальной нагрузки, поэтому даже при большей суммарной подаче в жидкой фазе наблюдается меньший свободный остаток O3 [9, 10].

Таблица 1. Сводное сравнение метрик базовой и обобщённой гибридной моделей

Показатель	Базовая модель	Обобщённая модель	Сравнение
Итоговая загрязнённость, мг/л	0,366 (C_p)	0,736 (C_poll)	Прямая сопоставимость условна
Итоговый растворённый озон, мг/л	0,252	0,100	Ниже на 60,4 %
RMSE, мг/л	0,493	0,780	Выше на 58,1 %
IAE, мг·ч/л	3,707	6,215	Выше на 67,7 %
Интегральный расход управления	2,616	4,751	Выше на 81,6 %
Пиковый O_3, мг/л	0,458	0,176	Ниже на 61,6 %

Следует отметить, что увеличение значений RMSE и IAE при использовании обобщённой модели не является признаком снижения эффективности алгоритма управления. Напротив, данный результат отражает увеличение информационной ёмкости модели. При переходе к многомерному описанию регулятор начинает учитывать перераспределение озона между несколькими независимыми каналами потребления, каждый из которых характеризуется собственной кинетикой реакции.

С инженерной точки зрения это означает переход от управления некоторым условным интегральным загрязнителем к управлению реальным многокомпонентным процессом. Именно поэтому полученные показатели характеризуют не ухудшение модели, а повышение степени её физической адекватности.

Подобный вывод хорошо согласуется с современными исследованиями цифровых двойников технологических объектов, в которых повышение размерности модели рассматривается как необходимое условие повышения достоверности прогнозирования [1].

Графики компонент обобщённой гибридной модели показывают, что суммарное загрязнение в процессе моделирования раскладывается на набор частных концентраций, которые по-разному взаимодействуют с озоном. Наиболее значимый вклад в остаточное загрязнение к концу расчёта вносит органическая составляющая, тогда как железо и марганец снижаются быстрее (рисунок 2). Это подтверждает, что обобщённая модель даёт не только итоговое значение качества воды, но и объясняет внутреннюю структуру процесса, что особенно важно для инженерной интерпретации и настройки анимационного интерфейса [4, 5, 7, 8].

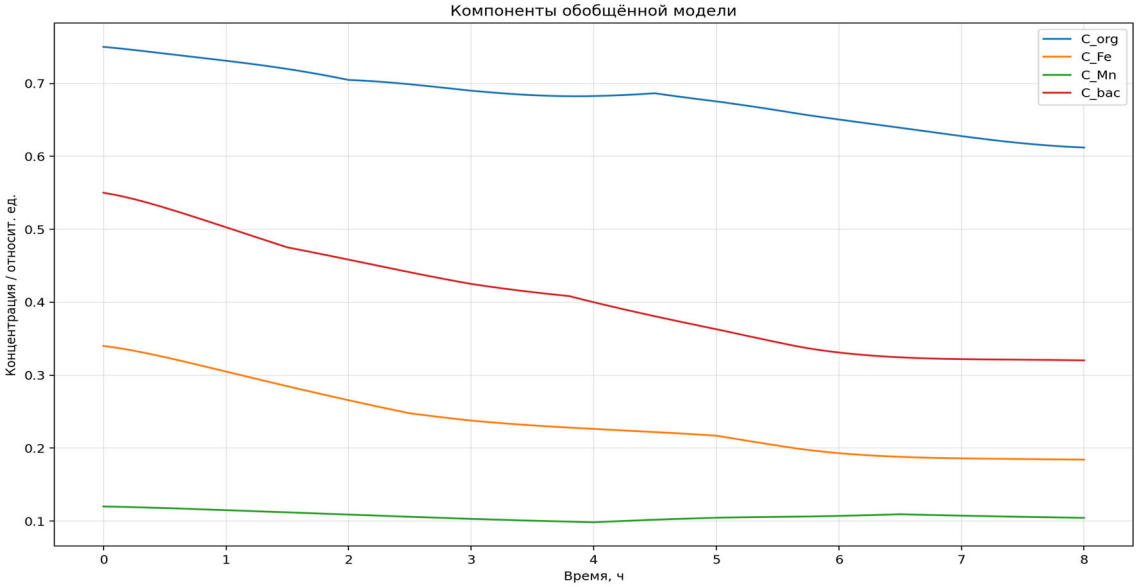

Рисунок 2. Поведение компонент обобщённой гибридной модели: суммарные загрязнители, органика, железо, марганец и бактериальная нагрузка

Сравнение управляющих воздействий в базовой и обобщённой гибридных моделях приведена на рисунке 3. Из анализа управляющих воздействий следует, что базовая модель формирует более экономичный режим подачи озона, однако этот результат достигается за счёт упрощённого представления загрязняющей нагрузки. В обобщённой модели регулятор вынужден поддерживать более высокий интегральный расход озона, поскольку должен компенсировать многоканальное потребление реагента. Следовательно, если задача состоит в создании демонстрационной или учебной анимации, базовая модель может быть достаточной. Если же требуется цифровой двойник, пригодный для интерпретации реального многокомпонентного состава воды, предпочтительна обобщённая гибридная модель [2, 3].

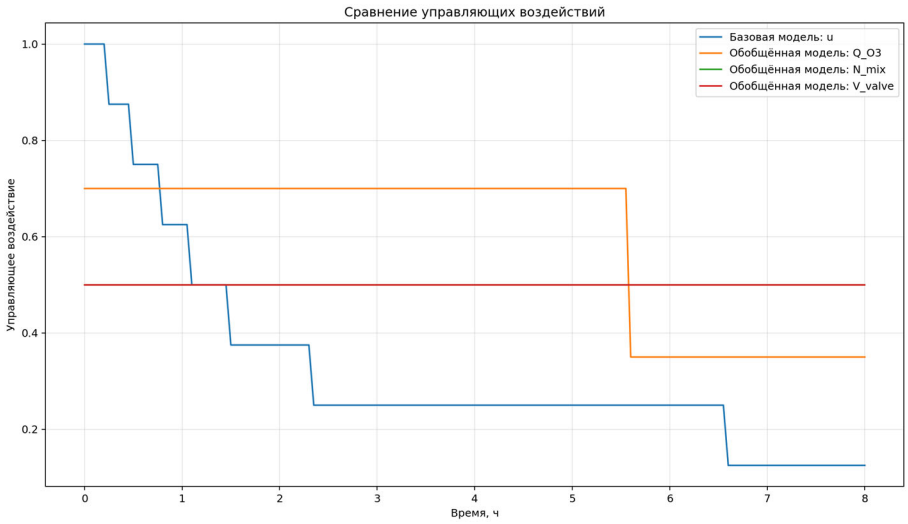

Рисунок 3. Сравнение управляющих воздействий в базовой и обобщённой моделях.

Полученные зависимости подтверждают, что обобщённая модель изменяет характер работы системы автоматического управления. Если в базовой модели практически весь

подаваемый озон расходуется на снижение единственного агрегированного показателя загрязнения, то в обобщённой модели происходит конкурентное распределение реагента между несколькими процессами окисления.

Поэтому даже увеличение суммарной подачи озона не приводит к росту концентрации свободного растворённого озона. Наоборот, большая часть реагента практически мгновенно вовлекается в химические реакции. Именно этим объясняется одновременное увеличение интегрального расхода управления и уменьшение максимальной концентрации остаточного озона.

С практической точки зрения данный результат является положительным, поскольку снижение пиковых концентраций растворённого озона уменьшает вероятность локальной переозонации и делает технологический режим более безопасным для эксплуатации оборудования и последующих стадий водоподготовки [4, 5].

На столбиковой диаграмме (рисунок 4) выполнено сопоставление ключевых количественных показателей базовой анимационной модели и анимационной модели, построенной с учётом обобщённой математической модели процесса озонной очистки воды. Данная диаграмма позволяет не только визуально оценить различия между моделями, но и интерпретировать, как усложнение математического описания влияет на качество регулирования, расход управляющего воздействия и характеристики озонного режима.

В качестве основных метрик сравнения были использованы: конечная концентрация загрязняющего компонента, среднеквадратическая ошибка регулирования, интегральная абсолютная ошибка, интегральный расход управляющего воздействия и пиковая концентрация растворённого озона. Эти показатели отражают разные стороны эффективности модели. Конечная концентрация характеризует итоговую глубину очистки. Среднеквадратическая ошибка показывает среднее отклонение управляемой величины от требуемой траектории. Интегральная абсолютная ошибка отражает суммарную ошибку за весь интервал моделирования. Интегральный расход управляющего сигнала характеризует общий объём управляющего воздействия, то есть суммарную нагрузку на контур подачи озона. Пиковая концентрация озона позволяет оценить степень форсирования процесса и риск локальной переозонации.

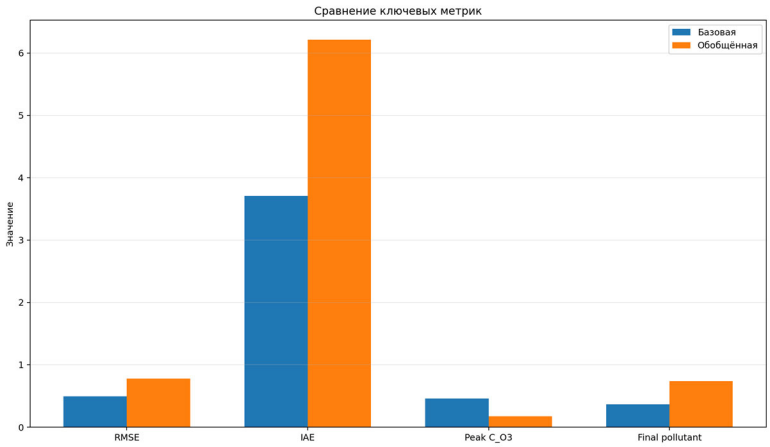

Рисунок 4. Столбиковое сравнение основных метрик двух моделей

Согласно полученным результатам, для базовой модели конечная концентрация загрязняющего вещества составила 0,366 мг/л, тогда как для обобщённой гибридной модели конечная суммарная концентрация загрязнителей составила 0,736 мг/л. Это означает, что при текущих настройках управления базовая модель демонстрирует более глубокую очистку по основной управляемой координате. Однако данный результат необходимо интерпретировать с учётом различий в самой структуре моделей. Базовая

модель описывает процесс в упрощённом виде и фактически работает с одной суммарной загрязняющей компонентой, тогда как обобщённая модель одновременно учитывает органические вещества, железо, марганец, бактериальную нагрузку, изменение pH и температурный режим. Следовательно, более высокая остаточная концентрация в обобщённой модели свидетельствует не столько о её меньшей эффективности, сколько о большей физической полноте описания и более жёстких условиях моделирования.

Среднеквадратическая ошибка регулирования для базовой модели составила 0,493, а для обобщённой — 0,780. Увеличение этого показателя в обобщённой модели показывает, что процесс управления в условиях расширенного набора состояний становится более сложным. Регулятору необходимо учитывать большее число взаимосвязанных факторов, а значит, поддержание требуемой траектории суммарного загрязнения требует более точной настройки. Аналогичная закономерность наблюдается и по интегральной абсолютной ошибке: для базовой модели её значение составило 3,707, а для обобщённой — 6,215. Это означает, что суммарное отклонение от желаемого режима в обобщённой модели оказалось выше. Причина состоит в том, что озон в этой модели расходуется не только на снижение суммарного загрязнения, но и на окисление отдельных компонентов воды, включая органику, железо, марганец и микроорганизмы.

Особенно показательной является метрика интегрального расхода управления. Для базовой модели она составила 2,616, а для обобщённой — 4,751. Таким образом, для поддержания процесса в расширенной модели потребовалось заметно большее суммарное управляющее воздействие. Это указывает на то, что обобщённая модель является более ресурсоёмкой и предъявляет более высокие требования к алгоритму дозирования озона. С инженерной точки зрения данный результат закономерен: чем больше факторов и реакционных каналов учитывается в системе, тем выше требуемая интенсивность управления для компенсации совокупной нагрузки.

Отдельного внимания заслуживает сравнение пиковой концентрации растворённого озона. Для базовой модели максимальное значение составило 0,458 мг/л, а для обобщённой — 0,176 мг/л. В отличие от предыдущих метрик, здесь преимущество наблюдается уже у обобщённой модели. Более низкий пик концентрации озона означает, что в расширенной модели озон распределяется и расходуется более равномерно между несколькими параллельными процессами: окислением суммарных загрязнений, органики, железа, марганца и обеззараживанием. Иными словами, базовая модель обеспечивает более быстрый рост концентрации озона в реакторе, тогда как обобщённая модель демонстрирует более сдержанный и физически реалистичный озоновый режим. Это важно с практической точки зрения, поскольку чрезмерно высокие пики озона могут быть нежелательны для реальной установки.

Таким образом, столбиковая диаграмма позволяет выполнить интегральное сравнение основных показателей эффективности обеих моделей. Полученные результаты демонстрируют закономерное увеличение ошибок регулирования и расхода управляющего воздействия при переходе к многокомпонентному описанию процесса.

При этом следует учитывать, что базовая модель работает с одной агрегированной переменной состояния, тогда как обобщённая одновременно описывает несколько независимых процессов окисления. Поэтому прямое сравнение абсолютных значений ошибок возможно лишь с учётом различий в физическом содержании моделей.

Наиболее важным результатом является существенное уменьшение максимальной концентрации растворённого озона в обобщённой модели. Данный эффект свидетельствует о более реалистичном распределении озона между реакционными каналами и подтверждает корректность выбранной структуры математической модели.

Современные алгоритмы Model Predictive Control используют внутреннюю математическую модель объекта для прогнозирования поведения системы на конечном горизонте управления. На каждом шаге рассчитывается оптимальная последовательность управляющих воздействий, минимизирующая целевую функцию при соблюдении технологических ограничений [2-5].

В рассматриваемой работе единая структура MPC применялась как для базовой, так и для обобщённой моделей. Благодаря этому различия в результатах моделирования обусловлены исключительно особенностями математического описания процесса, а не различиями в алгоритмах управления. Такой подход обеспечивает корректность сравнительного анализа и позволяет объективно оценить влияние полноты математической модели на качество интеллектуального управления[14].

Обсуждение

Полученные результаты свидетельствуют о том, что различия между исследуемыми моделями обусловлены не только различной размерностью пространства состояний, но и принципиально различным представлением физико-химической природы процесса озонирования. В базовой модели весь комплекс загрязняющих веществ представлен одной агрегированной переменной, вследствие чего регулятор воспринимает объект как систему с одним основным каналом потребления озона. Это приводит к более низким значениям ошибок регулирования и меньшему расходу управляющего воздействия.

В обобщённой модели озон одновременно расходуется на несколько параллельных процессов: окисление органических соединений, железа, марганца, инактивацию микроорганизмов, а также частично зависит от изменения кислотности среды и температуры. Поэтому даже при использовании одинаковой структуры регулятора объект управления становится существенно более сложным. Рост интегральных ошибок регулирования в данном случае следует рассматривать не как ухудшение эффективности управления, а как следствие более адекватного описания реальных процессов, протекающих в реакторе озонирования.

Полученные результаты хорошо согласуются с современными тенденциями развития интеллектуальных систем управления технологическими процессами. В настоящее время цифровой двойник рассматривается не только как средство визуализации, но и как инструмент поддержки принятия решений, прогнозирования аварийных ситуаций и оптимизации режимов работы оборудования [1-5]. Именно поэтому полнота математического описания объекта приобретает принципиальное значение.

Использование прогнозирующего управления MPC позволяет наиболее эффективно использовать преимущества обобщённой модели. Благодаря прогнозированию будущих состояний системы регулятор способен учитывать ограничения технологического процесса, перераспределение озона между отдельными реакциями и динамику изменения состава воды. Подобный подход существенно превосходит классические ПИД-регуляторы при управлении многомерными нелинейными объектами [9-18].

Заключение

В результате проведённого исследования выполнено комплексное сравнение базовой и обобщённой гибридных моделей процесса озонной очистки воды, используемых при построении интеллектуальной анимационной системы и цифрового двойника водоочистной установки. Анализ результатов моделирования показал, что базовая модель обеспечивает более низкие значения RMSE, IAE и интегрального расхода управляющего воздействия благодаря использованию упрощённого описания загрязняющей нагрузки[1,2,9].

В отличие от неё обобщённая модель учитывает многокомпонентный состав загрязнений, включающий органические вещества, железо, марганец, бактериальную

нагрузку, а также влияние кислотности среды и температуры. Благодаря этому она значительно точнее воспроизводит физико-химические механизмы потребления озона и позволяет получать более достоверное описание технологического процесса.

Полученные результаты показывают, что увеличение ошибок регулирования и расхода управляющего воздействия обусловлено прежде всего усложнением математического описания объекта, а не снижением эффективности интеллектуального алгоритма управления. Напротив, применение обобщённой модели позволяет существенно повысить информативность цифрового двойника и обеспечить более глубокий анализ состояния технологического процесса.

Научная новизна выполненного исследования заключается в сравнительном анализе двух уровней математического описания процесса озонной очистки воды в рамках единой интеллектуальной системы управления. В отличие от большинства известных работ, сравнение выполнено при одинаковой структуре MPC-регулятора, что позволило объективно оценить влияние исключительно математической модели на качество управления.

Практическая значимость работы определяется возможностью использования разработанной обобщённой модели в качестве вычислительного ядра цифрового двойника водоочистной установки, обеспечивающего интеллектуальную визуализацию технологического процесса, прогнозирование изменения качества воды и поддержку оператора при выборе оптимального режима озонирования[10,15].

В целом результаты исследования подтверждают целесообразность применения двухуровневой архитектуры интеллектуальной системы управления озонной очисткой воды. Базовая модель может использоваться для оперативного моделирования, разработки операторского интерфейса и обучения персонала благодаря высокой вычислительной эффективности. Обобщённая гибридная модель является более перспективной основой для построения цифрового двойника, обеспечивающего достоверное воспроизведение физико-химических процессов, поддержку принятия решений и последующую оптимизацию режимов работы водоочистной установки с использованием методов искусственного интеллекта.

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Sociological Sciences

Femina Academica, Female Professionals in Sociology

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Femina Academica as a concept, a research project idea, and book investigation theme is defined in 2016 (Spano), inside the Higher Educational Female Leadership position, precisely focused on towards female leadership inside Higher University positions. Femina Sociologica, Femina Ecologica, Femina Cartoonica, Femina Xenologica along with Femina Academica, and Femina Anima, constitute educative edition, dedicated to investigational research practices of Feminine identity in the Contemporary. Spano explains the importance of Female leadership through the notion of basis in legal documents. "The UNESCO (1998) Declaration on Higher Education" includes a statement that Higher Education (HE) 'should promote solidarity, and equity', and it also includes equality of access. Femina Academica, and Empowering of Women, in Higher Institutional Education, is complex, historically remarkable, and especially developed inside the contemporary professional female Sociology and, in American Sociology because of distinguished the Sociologists for Women in Society organisation, while in Europe we find less dominant female professional positions , and perplexities of selections of Females in Academia.
Key terms: Femina Academica, Black Feminist Sociology, Female Centred Sociology, Academic Conviviality, Feminist Eco criticism

Introduction

As a sub-discipline of Sociology, Professional Female Sociologists are a very significant theme inside the sub discipline of Sociology, that is extraordinary, multidisciplinary, based on a plural perspective , and important for to professional organisations as well. Theme Sister founders in Sociology is, a concept defined by Mary Jo Deegan, professor Emerita from Nebraska Lincoln University (USA). This concept , that is connected with to the demarcation, and reconstruction of female establishment in Sociology(Mušić 2014, 2017). Museum of famous today, Sister founders in Sociology, involve Ida Wells Barnett's Museum, Jane Addams's Museum , and Caroline Bartlett Crane's Museum. Well known for black feminism, and Sociology of Empowerment, and Black Female Emancipation, W.E.B. Du Bois, incorporated into his very celebrated Museum exhibits the multimedia representations inherited inside the freedom of Speech, Vote, and debates around the discrimination of Black Females.

"Du Bois's(Mušić 2022) limited views of black women, inhibit his ability to imagine African American women, as race leaders.)Du Bois's descriptions of black women unintentionally re-inscribed patriarchal ideals, as he sought racial equality. To Du Bois, black women held moral power, over men , and thrived in the domestic sphere" (24). "The Damnation of Women," similarly to this letter, Du Bois finds that black women's damnation lies in their inability to be deemed respectable, delicate, and worthy of the same admiration, as white women. Yet unlike his 1920 essay, the letter demonstrates that as of 1906, Du Bois had not yet articulated how racism affected black women's political, or economic standing. His analyses of race, and gender, were limited to black women's representation, and their need for protection. The founders action of Black feminist sociology, Ida Wells-Barnett, and Anna Julia Cooper, made Radical social change, in

biographies, history, and Sociology. They envisioned the African-American female life as superior, and as a contemporaries, they founded the sociology of African-American Women, which concentrated on were the special focus towards their real, and practical experiences.(Madoo, Lengermann, Niebrugge (1998:149-184). Marianne Weber, as a wife of Max Weber's wife, founded the idea of Women- centred sociology. Women centred Sociology is , organised around the female standpoint, especially in relation to importance on gender based ideology! She critiques the family structure, and especially working sphere, and domestic life, and " that societal harmony is made on the account of female autonomy" (Madoo, Lengermann, Niebrugge, Brantley, 1998:204). Weber argues: "That Women are framed in male-dominated society, with male dominated institutions of law, religion and history of series of male-made events, and by male-dominated analysis of the relations in between this institutions and this events."(1998:204). In her text, "The soil and air of the Academic life ," she writes about the concept of academic conviviality, describing the gatherings, in Heidelberg, of intellectuals, at Weber's family saloon, around the academic themes, decades after Weber died. She organised Sunday lectures, that looked like this: "the first hour was spent in unguided conversations, in small groups, with tea, and cakes. Then the guests settled down, to the talk, and discussion that followed, as vital elements of the intellectual Heidelberg. The scholars who participated, with their wives, were from all the faculties of the University, but most of them came from the Humanities, and Social Sciences(1977:4-5). Feminist Eco criticism, according to Vakoch's (2012)theory, represents the plural perspectives, that involves pleads of different, and even contradictory positions, since it is not subject of generalisations. Feminist Eco criticism, pinions forces Feminism, and Eco critics (feminist literature relation to the environment) into a creative, innovative, enhancing project of multiple perspectives in understanding the feminist , and Ecological structure in different-varying, and even opposed perceptions (Vakoch 2012).

"The origin of female exclusion in theory, in the work of the eco feminist Eislar Rian Eco feminist manifesto (1987) can be traced in following notions, that the social system of Minoan period of rule, on Greek island Crete, was the only true democracy. The Athenian democracy was the rule of the free aristocratic males. Women, and slaves (man and women of other colour) were marginalised, and excluded from public sphere. Only free males were subject to obligation of public speeches as a mark of true citizen. Patricia Shipley , holds that Aristotle's scripts on social system represent the origin of misogyny, and subordination of women, especially binary divisions: Femininity / masculinity, Nature / Culture, Emotion / Ratio, Subordination / Dominance, Logic of care/Logic of dominance, Pain /Pleasure. Small Albion advocates the doctrine of separate spheres, believing that men, and women are different distinctly, "separate but equal", comparing this difference to difference between two musical instruments, having the same relation to the notes in scale, but could not be replaced, or supply place in their own separate series (Deegan, 1981: 15).

Methodology

This analyses employs Comparative and historical methods as well as, the content analyses of textbooks , and materials in order to compare the female stream, and a male stream, in sociological approaches. Some of the methodological goals of this chapter include: the gender equal education, as a significant tool of postmodern education processes, and female stream textbooks involvement, inside the curriculum. During this process the interviews, with the eminent authors of the books, and writers of female sociologists biographies will be preformed (Mary Jo Deegan, prof.emerita Nebraska Lincoln University). The library and archival researches will be used are undertaken to analyses the accessibility of the literature on Female sociologists. Mary Jo Deegan, in 1990, wrote her significant study- source book on Women founders in sociology, describing 53 women founders in sociology. In the appendix of this work, refers to another even plus 66 women sociologists, who should be subject or are mentioned for further investigations.

These women are rarely mentioned, in male stream sociology. Only pro feminist masculine authors mention works of women in sociology. Peter J. Scott has written a study on *Fifty key sociologists,* but he only mentions three women. In comparison to Mary Jo Deegan's work on 118 female sociologists, this previously mentioned work is male stream and, even discriminating.

FEMALE SOCIOLOGY AS AN ACADEMIC DISCIPLINE

The importance of this project involves, being introduced into the introduction to the significant large amount of the literature, written in America about female sociologists(Mušić 2014, 2017, 2021). First female professional sociologists as speakers at ASA conferences: Ward supported the authorship, and academic activities of Charlotte Perkins Gilman, and supported the inclusion of women. Charlotte Perkins Gilman, as a respectful female sociologists, and economist, was even three times involved, as a discussant during the American Sociological Association (ASA) meetings. The first women included in first ASA meeting was Mrs J. Oldenwalrd-Unger. Small invited Jane Addams to speak as major a prominent speaker during 1911, 1912, and 1913 , at the ASA conferences. The other speakers were Lucy Salmon from Vassar College (1913), and Emily Greene Balch, from Wellesley College, in 1914 (Deegan , 198:16). But in some years , no women were included, because they did not hold important roles, in meetings. Ross invited s Jane Addams to speak on sociological aspects of War, and Militarism , in their sociological aspects, in 1915, but Emily Green Balch came instead of her, and spoke on Addams' behalf. , and the 1915 meeting become was a controversial meeting. Why was the meeting controversial? Addams and Balch were against war, and supported pacifism, and also were both Nobel Prize Winners. Jane Addams won the award in 1931, and Emily Green Balch in 1946. None of the men from Chicago school, wanted to discuss Addams' work. Consequently, after contacting fifteen male sociologists, Ross founded two women,: Lillian Wald (Head, residents of Henry Settlement, NYC) and Anna G. Spencer (Meadville Theological Seminar, Ohio), who would read Addams' papers. The fundamental sociological text, Hull House maps and papers, is published by Hull House residents in 1893, as a fundamental sociology paper:

"Focused on social change, they articulated the American dream, especially adapted to smart, educated anglo-women, who wanted a new role in life , and society. Addams(Mušić 2015) surrounded herself with brilliant, and dedicated people, especially women. These women formed a key group living, in the countryside, writing together, collecting statistics, examining factories and industries, examining health conditions, examining sanitary conditions, lobbying for legislative and political reforms, and organising social improvement in their overpopulated, immigrant district working class. Outside this vast and poorly organised space of activity, Addams was a charismatic leader, who translated "facts" , into everyday language, articulating the problems, and needs of the community and forming American ideals, and social thoughts. An author of eleven books, and hundreds of articles, Addams continued her efforts, in lectures, and education through lectures across the country, and at Hull House. She became a spokeswoman for her era, especially for women, and immigrants, of the working class. "(Deegan, 1990: 39). The origin of these houses, became popular in America, and one such was founded by Lillian Wald, Henry Settlement in New York, and a sociologist of neoadamsian Orientation, Caroline Bartlet Crane in Kalamazoo, Michigan. In the time before the beginning of the First World War, the Pacifist, Addams, was considered a good, and noble woman , to become a target of various animosities, and personal attacks, until the American accession to the war in 1913, when she became socially, and publicly marginalised, and after public celebration as a saint, she becomes publicly abused as a violent one."Intimidated by the excitement of speaker platforms, and abandoned by colleagues, and the most prominent, other sociologists / gypsies, Addams has socially become, a rogue band. That time was the agony's time for her. Dedicated to her values, basic, feminine ideals, she continued to advocate, her pacifist position. The culmination of her politically unbreakable status, occurred in 1919, when the US government

labeled her the most dangerous woman, in America. At that time, her role as a sociologist, which was the main one, was erased. "(Deegan, 1990: 40). After women gained the right to vote, in 1920, Addams, and many Suffragettes celebrated as the main victory, in the years to come after 1931, Addams again becomes the spokeswoman of the establishment of social security, and as a dying 1935 , was again mournful, around the world, as a great leader , and analyst of American social reality (Deegan, 1990: 40). Jane Addams, Charlotte P. Gilman (Deegan, Podeschi, 2001), Caroline B. Crane (Deegan, Rynbrandt, 2002). Sisters founders in sociology, advocated cultural feminism, and ecofeminist pragmatism. The inclusive momentum of all disputes, in her studies, was a disagreement between cultural feminism, and critical pragmatism.

Conclusion

Femina Academica, Women centred sociology, Academic conviviality, Black feminist sociology, Black male feminism, and Feminist eco criticism offer academic analysis, that is global, embracive, inclusive, wide ranging, and far reaching, in their academically distinguished results. Sociology of gender, uses all of thesis approaches, in distinguished, subversive, and always challenging approach.

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Contemporary Perspectives in the Evolution of Fashion Design

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Abstract:
The history of fashion design reflects societal values, technological progress, and cultural shifts from ancient civilisations to the modern digital era. From symbols of power in Egypt, Greece, and Rome, through elaborate medieval and Renaissance styles, to the revolutionary innovations of the Industrial Revolution and the dynamic trends of the 20th and 21st centuries, fashion has continually evolved as a means of self-expression, social status, and cultural identity. Historical styles, technological advancements such as 3D printing and digital textiles, and ongoing concerns about sustainability and ethics have a profound influence on modern design. Understanding this rich history enables designers to create innovative, meaningful, and responsible fashion that honours tradition while embracing future possibilities.
Keywords: fashion history, societal values, technological progress, cultural identity, ancient civilisations, Renaissance, industrial revolution, modern trends, sustainability, innovation, haute couture, digital textiles, social influence, design inspiration, cultural legacy

Introduction

The history of fashion design is a fascinating and complex story that offers insights into human civilisation, societal values, cultural identities, and technological progress. It is a narrative that spans thousands of years, from ancient times to the modern era, illustrating how clothing and style serve not only practical purposes but also symbolise power, status, cultural affiliation, and personal identity. The evolution of fashion reflects the broader social, political, and economic changes that societies have experienced over time, making it a vital aspect of understanding human history.

In ancient civilizations such as Egypt, Greece, and Rome, fashion was often a reflection of social hierarchy and authority. Luxurious garments, intricate jewelry, and elaborate accessories signified wealth and power, while simpler attire indicated lower social standing. Clothing was also deeply intertwined with cultural and religious practices, serving as a means of expressing spiritual beliefs and societal values. As societies progressed, fashion began to evolve alongside technological innovations, trade routes, and cultural exchanges, leading to the development of distinct regional styles.

The Middle Ages and Renaissance periods saw the emergence of more elaborate and ornate clothing, influenced by the social stratification of European society. The Renaissance, in particular, marked a rebirth of artistic expression, with fashion becoming a reflection of artistic trends, wealth, and political power. During these times, clothing became an important indicator of social status, with sumptuary laws regulating what individuals could wear based on their rank.

The Industrial Revolution in the 18th and 19th centuries brought about revolutionary changes in fashion production. The advent of mechanized textiles, sewing machines, and mass production techniques made clothing more accessible to a broader population. This era also saw the rise of haute couture in France, with designers beginning to craft unique, high-end garments that set new standards of style and innovation. Fashion became a means of personal expression, as well as a reflection of societal shifts such as urbanization and the rise of the middle class.

In the 20th century, fashion experienced rapid and dramatic transformations driven by technological advancements, cultural movements, and global influences. The post-World War II

era, for example, saw the emergence of youth culture and street fashion, which challenged traditional norms and introduced new styles that prioritized comfort, individuality, and self-expression. The rise of fashion icons, celebrities, and media further shaped trends and made fashion a powerful industry that influences millions worldwide.

Today, the fashion industry is more dynamic and diverse than ever before. The advent of digital technology has revolutionized how fashion is designed, marketed, and consumed. Social media platforms enable instant sharing of trends and styles across the globe, creating a truly interconnected fashion community. Contemporary trends such as streetwear, athleisure, and digital fashion reflect the changing preferences of younger generations, who value authenticity, sustainability, and innovation.

Sustainability has become a central concern in modern fashion, prompting designers and brands to rethink their practices to reduce environmental impact and promote ethical production. The increasing awareness of climate change, resource depletion, and social justice issues is shaping future directions in fashion design, emphasizing eco-friendly materials, circular economy principles, and fair labor practices.

In conclusion, the history of fashion design is an ever-evolving story that continues to mirror societal transformations, technological advancements, and cultural shifts. From ancient symbols of power to modern expressions of individuality and sustainability, fashion remains a vital and dynamic reflection of human identity. As we look to the future, understanding its rich history enables us to appreciate the ongoing innovations and challenges that shape this vibrant industry.

Ancient Civilisations and Their Legacy

The influence of ancient civilisations on modern fashion is profound and enduring. These early societies laid the foundations for many stylistic elements, symbols, and cultural values that continue to inspire contemporary design. Understanding their clothing traditions provides valuable insights into their social structures, spiritual beliefs, and cultural identities.

Egypt – A Symbol of Wealth and Spirituality

In ancient Egypt, fashion was not merely about aesthetics; it was deeply intertwined with spirituality and social hierarchy. Clothing served as a visual language that communicated an individual's social status, religious devotion, and connection to the divine. Pharaohs and the elite class wore opulent garments made from fine linens and richly decorated with gold, semi-precious stones, and intricate embroidery. These luxurious fabrics and adornments reflected their power, wealth, and divine right to rule.

Egyptian attire often carried religious symbolism. For example, the use of specific colors and motifs in clothing and jewelry was believed to invoke divine protection or favor. The famous broad collars, headdresses, and scepters were not only decorative but also held spiritual significance, representing authority and connection to gods such as Osiris and Isis. The elaborate jewelry, including necklaces, bracelets, and rings, was crafted from gold, carnelian, turquoise, and other stones, symbolizing life, protection, and eternity.

Moreover, clothing in ancient Egypt was designed to suit the climate, with men and women wearing simple linen garments suited for the hot desert environment. Yet, despite their simplicity, these garments were often decorated with symbols and patterns that conveyed religious and cultural messages. For example, the use of lotus flowers and papyrus motifs reflected the Egyptians' reverence for nature and the divine order.

Greece and Rome – Civilized Styles and Cultural Identity

The classical civilizations of Greece and Rome contributed significantly to the evolution of fashion, emphasizing both aesthetic beauty and social symbolism.

In ancient Greece, clothing was characterized by simplicity, elegance, and freedom of movement. The most common garments were the tunic, called the chitón, which was made from rectangular

pieces of fabric fastened with pins or belts. The chitón was often made from lightweight linen or wool, suitable for the Mediterranean climate. Its design allowed for various styles and ornamentation, reflecting the wearer's social status, gender, and occasion. Wealthier individuals might wear finely woven and embroidered chitónes, often dyed in vibrant colors.

Greek fashion was also marked by the use of draped garments such as the himation and peplos, which conveyed a sense of grace and civic pride. These garments were often decorated with intricate embroidery or painted patterns, showcasing the wearer's cultural identity and appreciation for artistry. The Greeks also used accessories like sandals, headbands, and jewelry to complement their outfits, often with symbolic meanings tied to religion and social status.

Roman fashion inherited many elements from Greece but adapted them to the empire's grandeur and practicality. Roman men commonly wore the tunica, a simple, functional garment, while women wore the stola, a long dress that signified modesty and social standing. The toga, perhaps the most iconic Roman garment, was a symbol of citizenship and political authority. Togas were often decorated with borders or embroidery to denote rank and social class. Roman clothing was not only about social distinctions but also about expressing power and civic identity. Wealthy Romans adorned their garments with elaborate embroidery, jewelry, and accessories such as fibulae (brooches) and belts. The practicality of Roman attire allowed for ease of movement and adaptability, suitable for the vast and diverse empire.

Legacy and Influence

The clothing styles of ancient Egypt, Greece, and Rome have left an indelible mark on the history of fashion. Their emphasis on symbolism, craftsmanship, and social distinction influenced subsequent periods, inspiring Renaissance textiles, neoclassical trends, and even modern design elements. For example, the draped elegance of Greek garments can be seen in contemporary evening gowns, while the opulence of Egyptian jewelry continues to inspire jewelry designers today.

Furthermore, the symbolic use of clothing as a marker of social and spiritual identity persists in modern fashion, from ceremonial attire to everyday fashion choices. The legacy of these ancient civilizations reminds us that clothing is much more than fabric; it is a powerful means of communication, cultural expression, and societal organization that continues to evolve and inspire.

Medieval and Renaissance Eras – Wealth and Symbolism in Fashion

Following the fall of Antiquity, the Medieval period brought significant changes to society, culture, and fashion. During this time, clothing began to be more closely associated with religious, feudal, and social structures. Fashion evolved from simple practicality to a powerful symbol of wealth, status, and identity, with its significance increasingly rooted in social hierarchy and cultural symbolism.

In early medieval times, clothing was primarily utilitarian, made from readily available natural fibers such as wool, linen, and leather. The garments were simple, modest, and functional, reflecting the modesty and austerity of the period. However, as trade routes expanded and technological advances in weaving and textile production developed, more elaborate and decorative garments started to appear among the wealthier classes. The introduction of intricate embroidery, decorative trims, and metallic accents signaled a shift towards fashion as a means of displaying affluence and social standing.Trade with Eastern countries played a crucial role in this evolution. Luxurious fabrics like silk, brocade, and damask became accessible to the nobility, often imported via long trade routes. These sumptuous materials allowed for the creation of more opulent clothing, which in turn became a visual marker of wealth and power. The wealthy could afford to adorn their garments with precious gemstones, pearls, gold embroidery, and elaborate patterns. Such embellishments were not only decorative but also served as symbols of prestige, divine favor, and political influence.During the late Middle Ages and beginning of the Renaissance, fashion

became even more elaborate, especially among the aristocracy. Clothing was designed to showcase wealth through intricate craftsmanship and luxurious materials. The garments of the nobility featured detailed embroidery, bejeweled accents, and rich textiles. These outfits often included accessories such as elaborate headpieces, jewelry—like necklaces, rings, and brooches—and decorative belts, all of which reinforced social hierarchy and status.

The Renaissance period marked a significant shift toward individuality and artistic expression in fashion. Clothing styles became more fitted and tailored, emphasizing the human form. Fabrics like velvet, silk, and brocade gained popularity, often decorated with elaborate embroidery, gold leaf, and vibrant dyes. The use of bright colors and complex patterns reflected not only wealth but also cultural sophistication and aesthetic ideals of beauty(Girard,2024). Fashion was increasingly seen as a form of art, with clothing serving as a canvas for artistic creativity and social symbolism.In both the Medieval and Renaissance eras, clothing was more than just a covering; it was a language of power, wealth, and cultural identity. Sumptuous garments and jewelry acted as visual markers of social rank and personal achievement. The ornate dresses, cloaks, and accessories worn by the elite communicated their importance and distinguished them from lower classes, who wore more modest and utilitarian attire.Overall, the Medieval and Renaissance periods laid the foundation for modern notions of fashion as a reflection of social status and cultural values. The technological advances, trade in exotic textiles, and artistic innovations of these eras made clothing a potent symbol of wealth, power, and identity—elements that continue to influence fashion today. Their legacy reminds us that clothing is not only about aesthetics but also about expressing societal roles, cultural values, and individual personality through visual means.

Early Modern Period and the Birth of Modern Fashion Styles

The 15th and 16th centuries marked a transformative era in the history of fashion, characterized by the emergence of distinct styles and the establishment of the first fashion houses. During the Renaissance, fashion began to become more specialized and varied, reflecting social class, geographical regions, and cultural influences.

This period saw a significant development in craftsmanship and technological innovation, which allowed for the production of more colorful, high-quality, and intricate garments. Textile production advanced with the improvement of weaving techniques and the availability of new dyes, making it possible to create vibrant, durable fabrics. As a result, clothing became a powerful means of expressing social status, wealth, and personal identity.

Moreover, the 15th and 16th centuries witnessed the rise of the first fashion houses and ateliers—early versions of modern fashion studios. These establishments started to design and produce collections of clothing that catered to the tastes of wealthy clients, aristocrats, and monarchs. The creation of these collections marked the beginning of fashion as a specialized industry, with designers and tailors working closely to develop new styles and trends.

Fashion during this era was also influenced by the cultural and artistic movements of the Renaissance, leading to more elaborate and sophisticated garments. Rich embellishments, luxurious fabrics, and detailed ornamentation became hallmarks of fashionable attire. These innovations laid the foundation for the modern fashion industry, which continues to evolve today, driven by creativity, craftsmanship, and the desire to express individual style.

In summary, the 15th and 16th centuries were pivotal in shaping the modern concept of fashion, transitioning from simple clothing to a refined and diverse industry with its own designers, collections, and cultural significance.

17th and 18th Centuries: Baroque, Rococo, and the Victorian Era

The 17th and 18th centuries were periods of dramatic change and opulence in fashion, marked by distinct styles such as Baroque, Rococo, and the early Victorian era. These eras reflected the social, political, and artistic currents of their times, emphasizing extravagance, ornamentation, and social

symbolism.During the Baroque period (early 17th century), fashion was characterized by grandeur and drama. Clothing featured rich fabrics like velvet, silk, and brocade, often decorated with elaborate embroidery, lace, and gold accents. The silhouette was voluminous, with wide sleeves, ruffled collars, and heavily ornamented garments that showcased wealth and power. Fashion served as a display of status, often reflecting the ornate artistic style of the Baroque movement.The Rococo era (early to mid-18th century) continued the theme of extravagance but introduced a lighter, more playful aesthetic. Fashion became even more decorative, with intricate lace, ribbons, and pastel colors. Wide panniers and hoop skirts created highly structured and voluminous silhouettes, emphasizing elegance and refinement. Clothing was designed to impress and dazzle, with elaborate embellishments and delicate details that highlighted craftsmanship. The styles of this period often reflected the aristocratic courtly life and the desire for beauty and sophistication.

In contrast, the Victorian era (mid-19th century) marked a shift toward more practical and modest fashion, driven by social and cultural values of morality and propriety. Early Victorian clothing still retained some ornate features, such as corsets, bustles, and decorative trims, but overall, there was a move towards more covered and structured garments. The emphasis was on neatness, modesty, and social symbolism—clothing was a sign of one's social class and moral standing. Fabrics and designs became more restrained, yet still detailed, reflecting the era's focus on decorum and social hierarchy. Throughout these centuries, fashion was intricately linked to societal roles, power structures, and artistic trends (Breward, 2023). From the grandeur of Baroque and Rococo to the more subdued yet symbolically rich Victorian styles, these periods laid the groundwork for modern fashion, demonstrating how clothing can serve as a reflection of cultural values and social identity.

19th Century: The Industrial Revolution and Mass Production

The 19th century was a transformative period for fashion, driven by the sweeping changes brought about by the Industrial Revolution. This era marked a shift from handcrafted clothing to large-scale, automated manufacturing processes, which significantly lowered costs and made fashionable clothing accessible to broader social classes.Advancements in technology played a crucial role. The invention of the steam engine, mechanized weaving, and dyeing techniques enabled the production of vibrant, durable, and high-quality fabrics and garments. These innovations led to the proliferation of ready-made clothing and the rise of department stores, which further democratized fashion by offering a wide range of styles at affordable prices.A notable development during this period was the emergence of haute couture in Paris. The first exclusive fashion houses dedicated to bespoke, high-end clothing began to appear. These ateliers emphasized craftsmanship, originality, and high-quality materials. Designers like Charles Frederick Worth, Jean-Paul Gaultier, and Coco Chanel laid the foundation for the modern luxury fashion industry, blending artistry with mass production techniques.The 19th century also saw the rise of fashion as a symbol of social status and identity, with styles evolving rapidly to reflect societal changes. The era's fashion was characterized by elaborate dresses, corsets, crinolines, and accessories that showcased wealth and sophistication.In summary, the Industrial Revolution revolutionized how clothing was made and consumed, transforming fashion into a more accessible, diverse, and technologically advanced industry. The establishment of haute couture set the stage for future innovation and luxury in fashion.

20th Century: Revolution in Style and Technology

The 20th century was marked by dramatic shifts in fashion, driven by technological innovations, social upheavals, and cultural movements (Giraldi, 2023). It was an era of experimentation, freedom, and rapid change, reflected in diverse styles from Art Deco to minimalist trends.

Fashion icons like Coco Chanel, Yves Saint Laurent, and Christian Dior revolutionized the industry with new silhouettes, fabrics, and concepts of elegance. The interwar period introduced minimalist

styles that emphasized simplicity and comfort, mirroring societal shifts toward individualism and emancipation.

The post-World War II era saw the rise of prêt-à-porter (ready-to-wear), making fashionable clothing more accessible than ever. The development of television, film, and later the internet transformed fashion into a global phenomenon. Pop culture and youth movements influenced styles such as hippies, punk, grunge, and streetwear, reflecting social and political sentiments.

Technological innovation continued to shape fashion. The advent of 3D printing, digital textile printing, and virtual fitting technologies revolutionized design, manufacturing, and shopping experiences. Virtual fashion shows and online boutiques expanded the reach of brands and consumers worldwide.

Contemporary Trends and Future Challenges

Today, fashion is increasingly focused on sustainability, inclusivity, and technology. Digital fashion, which exists in virtual worlds and online platforms, is gaining popularity. Streetwear influences high fashion, creating a fusion of casual and luxury styles. Environmental concerns have led to a push for eco-friendly materials, recycling, and transparent supply chains.Looking ahead, the industry faces challenges such as reducing waste, minimizing environmental impact, and ensuring ethical production. Technologies like artificial intelligence, virtual reality, and blockchain are transforming how clothes are designed, marketed, and sold. Virtual try-ons, digital fashion shows, and blockchain-based authenticity are reshaping consumer experiences (Poon 2017).

In conclusion, the 20th century set the stage for a dynamic and innovative fashion landscape. Today's focus on sustainability, digital transformation, and global interconnectedness promises an exciting future where fashion continues to evolve as a reflection of society's values, creativity, and technological progress.

Conclusion

The history of fashion design is a vibrant reflection of our society, its values, technological advancements, and cultural evolution. From ancient civilisations to the Renaissance, the Industrial Revolution, and the current digital era, fashion has continuously transformed, yet it remains a powerful means of self-expression, social identity, and cultural dialogue. Understanding this rich history allows designers and consumers alike to appreciate not only the beauty and originality of clothing but also the responsibility we bear as creators and users of fashion.

This historical perspective influences contemporary design in numerous ways. For example, designers often draw inspiration from past eras to create modern reinterpretations, blending vintage aesthetics with innovative techniques. The revival of 19th-century silhouettes, such as corsets or Victorian lace, can be seen in today's fashion collections, reimagined with sustainable fabrics or technological enhancements like 3D printing. Similarly, the bold, elaborate ornamentation of Baroque or Rococo styles inspires contemporary haute couture and runway shows, emphasizing craftsmanship and artistry.

Moreover, the technological innovations of the 20th and 21st centuries—such as digital fabric printing, virtual fitting rooms, and AI-driven design tools—are deeply rooted in the historical drive for innovation. These advancements enable designers to experiment more freely, push creative boundaries, and produce more sustainable and inclusive fashion. For example, brands like Adidas and Gucci are experimenting with 3D-printed accessories and virtual clothing lines, reflecting a fusion of historical craftsmanship and cutting-edge technology.

The ongoing emphasis on sustainability and ethical production is also influenced by historical lessons about resource use and social responsibility. The industrialization of fashion taught us about environmental impacts and labor issues, prompting modern designers to prioritize eco-friendly materials, transparent supply chains, and circular fashion models. Brands like Patagonia

and Stella McCartney exemplify this approach, integrating historical awareness with modern innovation to create more responsible fashion.

In essence, the historical journey of fashion design provides a foundation for creativity and innovation today. It encourages us to honor traditional techniques while embracing new technologies and values. By studying the past, designers can develop unique, meaningful, and sustainable collections—ensuring that fashion continues to evolve thoughtfully, reflecting both our heritage and future aspirations.

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Technical Sciences

USING SOIL MICROORGANISMS TO ASSESS HEAVY METAL POLLUTION IN CENTRAL KAZAKHSTAN

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Abstract: Anthropogenic pollution of urban ecosystems with heavy metals poses a serious threat to both nature and human health. Since the soil is the foundation of agricultural production and an integral part of the human life cycle, monitoring its condition is extremely important. The study analyzed the concentrations of lead, mercury, and the determination of humus in the soils of a number of cities in Central Kazakhstan for 2025-2026. The presented data can become the basis for systematic monitoring of land and the development of strategies to reduce pollution. This research has been funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP25796771).

Keywords: industrial ecology, heavy metals, microorganisms, bioindication, Central Kazakhstan

ИСПОЛЬЗОВАНИЕ ПОЧВЕННЫХ МИКРООРГАНИЗМОВ ДЛЯ ОЦЕНКИ ЗАГРЯЗНЕНИЯ ТЯЖЁЛЫМИ МЕТАЛЛАМИ В ЦЕНТРАЛЬНОМ КАЗАХСТАНЕ

Аннотация: Антропогенное загрязнение городских экосистем тяжелыми металлами представляет серьезную угрозу как для природы, так и для здоровья людей. Поскольку почва выступает фундаментом сельскохозяйственного производства и неотъемлемой частью жизненного цикла человека, контроль за ее состоянием крайне важен. В исследовании проанализированы концентрации свинца, ртути, а также определение гумуса в почвах ряда городов Центрального Казахстана за 2025-2026 годы. Представленные данные могут стать базой для системного мониторинга земель и разработки стратегий по снижению уровня загрязнения. Данное исследование финансировалось Комитетом науки Министерства науки и высшего образования Республики Казахстан (грант № AP25796771).

Ключевые слова: промышленная экология, тяжелые металлы, микроорганизмы, биоиндикация

ОРТАЛЫҚ ҚАЗАҚСТАНДАҒЫ АУЫР МЕТАЛДАРДЫҢ ЛАСТАНУЫН БАҒАЛАУ ҮШІН ТОПЫРАҚ МИКРООРГАНИЗМІН ПАЙДАЛАНУ

Аннотация: Қалалық экожүйелердің ауыр металдармен антропогендік ластануы табиғатқа да, адамдардың денсаулығына да үлкен қауіп төндіреді. Топырақ ауылшаруашылық өндірісінің негізі және адамның өмірлік циклінің ажырамас бөлігі болғандықтан, оның жағдайын бақылау өте маңызды. Зерттеуде қорғасын, сынап концентрациясы, сондай-ақ 2025-2026 жылдардағы Орталық Қазақстанның бірқатар қалаларының топырақтарындағы гумустың анықтамасы талданды. Ұсынылған деректер жерді жүйелі мониторингтеу және ластану деңгейін төмендету стратегияларын әзірлеу үшін негіз бола алады.

Бұл зерттеуді Қазақстан Республикасы Ғылым және жоғары білім министрлігінің Ғылым комитеті қаржыландырды (грант № AP25796771)

Түйінді сөздер: Өнеркәсіптік экология, ауыр металдар, микроорганизмдер, биоиндикация

Кіріспе

Микроорганизмдер топырақтағы ауыр металдардың пайда болуына өте тез жауап береді, сондықтан оларды ластанудың "тірі датчиктері" ретінде пайдалануға болады. Ауыр металдардың көбеюімен Органикалық заттардың ыдырауына және гумустың пайда болуына жауап беретін пайдалы гетеротрофты микроорганизмдердің саны азаяды. Сонымен қатар, қоршаған ортаның қолайсыз жағдайларына жақсы бейімделген олиготрофты микроорганизмдердің үлесі артады. Микроорганизмдердің осы топтарының арақатынасының өзгеруіне байланысты топырақтың ластану дәрежесін және экологиялық стресс деңгейін бағалауға болады. Осылайша, микроорганизмдер химиялық немесе сыртқы белгілері байқалмай тұрып-ақ топырақтағы жағымсыз өзгерістерді анықтауға мүмкіндік береді.

Қазіргі уақытта қоршаған ортаға ауыр металдардың шығарындылары табиғи ғана емес, сонымен қатар антропогендік болып табылады. Оларға өнеркәсіптік қалдықтар, тау-кен өндірісі, көлік, түсті және Қара металдар өндірісі, құрамында ауыр металдар бар тыңайтқыштарды таңдамай пайдалану, жылу электр станциялары (ЖЭС) немесе жалпы урбанизация жатады. Көптеген ауыр металдар, соның ішінде қорғасын, кадмий, хром, никель және сынап улы. Ғалымдардың пікірінше, кадмий мен қорғасын барлық жерде кездеседі және әсер ету дәрежесі бойынша бірінші сыныпқа жатады. Бұл элементтердің кез-келген мөлшері адам ағзасына өте қауіпті және тірі организмдердегі метаболизмнің әртүрлі бұзылуларына әкеледі. MGF антиоксидантты, апоптотикалық, бейтараптандыратын радикалдар және хелат түзетін қасиеттер сияқты әртүрлі әсерлерге ие. Бұл бағалы металдарды алу және кәдеге жарату үлкен маңызға ие. Су қоймасының үш аймағында ТМ қоспағанда, ауыр металдардың шамалы ауытқуы байқалды, бұл айтарлықтай айырмашылықты көрсетті. Көптеген ауыр металдар қандай да бір жолмен уыттылыққа ие болғандықтан, адам өлімі мен экологиялық апаттардың алдын алу үшін оларды үнемі бақылау қажет. Тұтас бидай ұнының канцерогенді емес орташа тәуліктік дозасы (ADD) мен бидай ұнын тұтыну арасындағы қатынас 1,06-дан 3,76-ға дейін өзгерді, Pb басқа металдармен салыстырғанда ең жоғары мәндерге ие болды. Әр түрлі металдарға ең қолайлы кинетикалық модель әр түрлі болды. Мысалы, қоршаған орта факторлары немесе ауыр металдар бриофиттердің таралуына тиімді әсер етеді. Қалалық су алаптарынан төмен қарай жайылмалар ықтимал улы микроэлементтердің ағындары болып табылады. Жанармай жағатын қондырғылардың түтін газдарын зерттеу олардың құрамында ауаның негізгі ластаушылары көміртегі оксидтері (50% дейін), күкірт оксидтері (20% дейін), азот

оксидтері (6-8% дейін), көмірсутектер (5-20% дейін), күйе, оксидтер және көмірсутек отындарындағы минералды қоспалар мен қоспалар. Шығарылатын, шығарылатын және шығатын газдармен бірге көмірсутек отынының жануы нәтижесінде пайда болатын барлық жылудың шамамен 60-80 пайызы атмосфераға ыстық газдар мен қыздырылған су түрінде шығарылады, бұл атмосфераның жылумен ластануына әкеледі. Сонымен қатар, шығарындылар ұйымдастырылмаған болып бөлінеді, Жабдықтың техникалық ақауларының нәтижесінде атмосфераға бағытталмаған газ ағындары түрінде түседі және ұйымдастырылған - арнайы салынған қондырғылар арқылы түседі, бұл экономикалық тұрғыдан тиімді және экологиялық таза. Ластаушы заттардың өзін бірнеше кластарға бөлуге болады: жергілікті, жарамдылық мерзімі қысқа және шағын аумаққа тән, бірақ соған қарамастан ең көп таралған; аймақтық - аймақ ішінде кең таралған және сақтау мерзімі сәл ұзағырақ. Консервативті емес ластаушы заттар Ұшпа, үнемі физикалық және химиялық процестерге ұшырайды және басқа заттарға айналуы мүмкін, көп немесе аз улы [19].

Жұмыстың мақсаты Орталық Қазақстан топырағындағы зиянды элементтер мен металдардың құрамын анықтау болып табылады.

Зерттеу материалы мен әдістері.

Зерттеу нысаны Астана, Көкшетау, Қарағанды және Теміртау сияқты Ақмола облысының қалаларының топырағындағы ауыр металдардың құрамы, сондай-ақ 2026 жылы 2025 жылға қарай құрамының арақатынасы болып табылады. Ауыр металдардың, сондай-ақ қарашірік пен микроорганизмдердің құрамын анықтау үшін топырақ сынамалары алынды.

Сарапшылар атап өткендей, бұл үш фактор азот диоксиді, көміртегі тотығы, күкірт диоксиді, формальдегид, күкіртсутек, тоқтатылған бөлшектер, фенол және аммиак сияқты ластаушы заттармен елді мекендерде атмосфералық ауаның ластануының жоғары және өте жоғары деңгейіне ықпал етеді. Осы тармақтарды толығырақ қарастырайық:

1. Өнеркәсіптік кәсіпорындардың шығарындыларын тарату-өнеркәсіптік өнімдерді жағу кезіндегі өндірістік процестердің нәтижесі атмосфералық ауаның ластануының жоғары деңгейін тудыратын зиянды заттардың барлық тізімі болып табылады. Олардың елді мекендер аумағынан жоғары ауа бассейнінде таралуы қалалардың, қала маңындағы және қалалық типтегі кенттердің атмосфералық ауасының сапасына айтарлықтай әсер етеді.

2. Жолдардың қалалық көлікпен шамадан тыс жүктелуі - көлік құралдарынан бензин мен дизель отынының көп компонентті шығарындылары елді мекендердегі ауаның азот диоксиді, көміртегі тотығы және органикалық заттармен ластануының негізгі көздерінің бірі болып табылады, сонымен қатар жақсы желдетілетін қалаларда да жолдардың кептелісі жоғары.

3. Елді мекендердің атмосфералық кеңістігінің төмен желдетілуі-ауадағы ластаушы заттар атмосфераның беткі қабатында жиналады және олардың концентрациясы өте жоғары деңгейде қалады. Көміртегі тотығы CO, жоғарыда айтылғандай, отындағы көміртегі толық жанбаған кезде түзіледі. Пештің қақпағы тым ерте жабылған кезде (көмір біржола күйіп кеткенше) пеште де осындай қалыптасу болады).

Нәтиже және талқылау.

Тапсырманы орындау шеңберінде Орталық Қазақстан — Астана, Қарағанды, Теміртау және Көкшетау қалаларында топырақ сынамаларын іріктеу және талдау жүргізілді. Іріктеу әр түрлі функционалды аймақтарда жүзеге асырылды: өндірістік, көлік, тұрғын үй және фондық аумақтар, бұл алынған мәліметтердің сенімділігі мен өкілдігін қамтамасыз етті. Сынама алу орындары: Астана-ЖЭО-2 (Индустриалды парк), ЖЭО — 3, Көктал, Тұран (Ailand) аудандары; Қарағанды-құю-машина жасау зауыты, ЖЭО-3 (50-100 м), орталық саябақ, көк тоғандар (фон); Теміртау-металлургия комбинаты (100 м), қала орталығы (тұрғын аймақ), шеті (фон);

Көкшетау — автожолдар бойында, ЖЭО, қала орталығы, фондық учаскелер. Ауыр металдардың (Pb, Hg, CD, as) және фтордың (F) құрамына химиялық талдау жүргізілді, сондай-ақ топырақ жағдайын биоиндикациялау үшін гумустың құрамы мен гетеротрофты микроорганизмдердің саны анықталды.

Нәтижелер мынаны көрсетті:

топырақтағы қорғасын (Pb) 1,6-дан 151,0 мг/кг-ға дейін өзгереді, бұл ретте ең Үлкен мәндер Теміртау мен Астанада тіркеледі, сынап (Hg) және Фтор (F) негізінен өнеркәсіп аудандарында айтарлықтай мөлшерде болады, қалалардың орталық бөліктері мен шеттерінде 0,3 шегінде көрсетіледі-1,2 мг / кг, бұл ластанудың рұқсат етілген деңгейіне сәйкес келеді;

көптеген сынамаларда Кадмий (Cd) табылған жоқ, жекелеген үлгілерде (Теміртаудың өнеркәсіптік аймақтары) құрамы 0,5 мг/кг аспайды, бұл санитарлық нормативтер шегінде;

Мышьяк (As) Теміртау қ. топырақтарында жоғары мәндермен 0,5-тен 3,0 мг/кг-ға дейінгі орташа концентрацияда анықталды, бұл металлургиялық кешеннің жергілікті әсерін көрсетеді; зерттелген үлгілердегі гумустың мөлшері 0,5-тен 5,3% - ға дейін өзгереді: жоғары мәндер гетеротрофты микроорганизмдердің Саны Қарағанды және Теміртау топырақтарына тән шамамен 10^7-10 сухой Бір / г құрғақ топырақ. ал Астана мен Көкшетаудың қала маңындағы және өнеркәсіптік аймақтары үшін төмен көрсеткіштер анықталды.

Көкшетау қаласының топырағындағы ауыр металдардың құрамын және 2026 жылы ауыр металдардың құрамының 2025 жылға қатынасын зерттеу нәтижелері 1-кестеде келтірілген.

Мысқа арналған шыны зауыттарында шекті рұқсат етілген концентрациядан асып кету байқалды – 2,1 ШРК.

Көкшетауда алынған топырақ сынамаларындағы ауыр металдардың мөлшері нормадан аспайды (1-Сурет). Көкшетау қаласында әртүрлі өңірлерден алынған топырақ сынамаларында хром мөлшері 0,0036 - 0,02 мг / кг, мыс - 0,3 - 20,0 мг / кг, қорғасын - 15,2 – 28,2 мг / кг, мырыш - 0,3 - 1,2 мг / кг, кадмий - 0,2 - 1,3 мг / кг. Көкшетау қаласында алынған топырақ сынамаларындағы басқа ауыр металдардың мөлшері нормадан аспады.

Қорытынды.

Жұмыс аймағының ауасын қажетті шектерде ұстаудың негізгі техникалық шаралары мен құралдарына мыналар жатады:

1. Ауаның ластануын барынша азайтуға мүмкіндік беретін ұтымды сәулет-жоспарлау шешімдерін таңдау;

2. Жұмыс бөлмелеріне ылғалдың, зиянды булардың, газдардың, аэрозольдердің бөлінуіне, сондай-ақ қызып кеткен және суық ауаның берілуіне байланысты операцияларды қоспағанда, технологиялық процестерді ұтымды ұйымдастыру;

3. Жұмысшылардың зиянды заттармен байланысын болдырмауға мүмкіндік беретін өндірісті механикаландыру мен автоматтандыруды кеңінен қолдану;

4. Жұмыс аймағында қолайлы жағдай жасауды қамтамасыз ететін тиімді жылыту, желдету және ауаны баптау жүйелерін қолдану;

Осы тезисті орындау барысында мен келесі тұжырымдар жасадым. Қазіргі уақытта зиянды газ шығарындыларымен күресудің төрт әдісі бар:

- отынның жану процестерін оңтайландыру;
- ластаушы заттардың көзі болып табылатын элементтерден отынды тазарту;
- түтін газдарын ластаушы заттардан тазарту;

2025 жылмен салыстырғанда 2026 жылы бұл қалаларда топыраққа ауыр металдар шығарындылары көлемінің төмендеуі байқалады. Зиянды газдардың көлемін азайтудың бұл тәсілдері аймақтың экожүйесін оңтайлы жағдайда ұстауға көмектеседі.

Қаржыландыру.

Бұл зерттеуді Қазақстан Республикасы Ғылым және жоғары білім министрлігінің Ғылым комитеті қаржыландырды (грант № AP25796771)

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НЕЙРО-АДАПТИВНОЕ УПРАВЛЕНИЕ ИННОВАЦИОННЫМИ ПЕРЕХОДАМИ: КОНЦЕПТУАЛЬНАЯ РАМКА НА ОСНОВЕ АДАПТИВНОГО УПРАВЛЕНИЯ, COLLABORATIVE ADAPTIVE MANAGEMENT И НЕЙРОАРХИТЕКТУРЫ

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Аннотация

Статья представляет концептуальную рамку нейро-адаптивного управления инновационными переходами. Основанием для синтеза выступают загруженные источники по adaptive management, collaborative adaptive management, adaptive governance и neuro-adaptive architecture. Цель статьи состоит не в доказательстве прямого влияния нейроархитектурной или акустической среды на результативность стартапов, а в уточнении доказательной базы, ограничений и исследовательского пробела для последующей DBA-диссертации. В статье показано, что adaptive management следует понимать как формализованное обучение через действие, мониторинг и корректировку, а не как обычную пробу и ошибку. Collaborative adaptive management раскрывает роль сложности, компромиссов, временных лагов и разных типов знания в формировании социального обучения. Adaptive governance добавляет организационный уровень анализа, где центральными становятся чувствительность организации к среде, координация и способность к адаптации. Neuro-adaptive architecture позволяет поставить вопрос о физиологическом состоянии лиц, принимающих решения, через такие осторожно интерпретируемые показатели, как HRV. Итогом является исследовательская модель, в которой среда рассматривается как потенциальное условие поддержки адаптации, но не как доказанный фактор успеха инновационных команд. Казахстанский контекст представлен как будущая область эмпирической проверки, а проект Audiotheatre — как возможный exploratory case.

Ключевые слова

нейро-адаптивное управление; инновационные переходы; adaptive management; collaborative adaptive management; adaptive governance; нейроархитектура; акустическая среда; HRV; аллостатическая нагрузка; DBA; Казахстан.

Введение

Инновационный переход в проекте или стартапе обычно связан с высокой неопределенностью: меняются цели, ресурсы, ожидания участников, доступность данных и критерии успеха. В настоящей статье этот фокус рассматривается как исследовательский замысел будущего DBA-этапа, а не как уже подтвержденный эмпирический результат. Поэтому любые положения о когнитивной нагрузке, командной синхронизации, акустической среде и Audiotheatre соотносятся не с неопубликованным авторским

проектом, а с проверяемой академической литературой, представленной в загруженных источниках.

Загруженные источники показывают, что литература по adaptive management уже содержит развитый язык для анализа решений в условиях неопределенности. Allen et al. (2011) подчеркивают, что adaptive management не является обычным trial-and-error, поскольку предполагает постановку целей, формулирование альтернатив, гипотезы причинности, сбор данных, оценку и повторение цикла. Rist et al. (2012), напротив, показывают, что термин adaptive management часто употребляется слишком широко: в их обзоре только небольшая часть публикаций фактически сообщала о внедрении подхода, а многие авторы не давали строгого определения понятия.

Для настоящей статьи это создает важное методологическое требование: нельзя механически переносить термины adaptive management, нейроархитектура или acoustic ecology в инновационный менеджмент без операционализации. Поэтому статья построена как концептуальный синтез с четким разграничением между тем, что подтверждено загруженными источниками, тем, что является авторской теоретической интерпретацией, и тем, что требует будущей эмпирической проверки.

1. Методологическая позиция статьи и проверка источников

Материал статьи ограничен загруженной документацией. Внутритекстовые ссылки и список литературы приведены только по источникам, представленным в загруженных файлах, а также по базовым первоисточникам, которые прямо указаны в списках литературы этих загруженных работ. Статьи Allen et al. (2011), Rist et al. (2012), Fernández-Giménez et al. (2019), Scarlett (2013) и Van Assche et al. (2022) используются как академическая база по adaptive management, collaborative adaptive management и adaptive governance. Первоисточники Holling (1978), Walters (1986), Walters and Hilborn (1978), Walters and Holling (1990), Lee (1993), Argyris and Schön (1978), Bandura (1977), Luhmann (1964, 2018) и Teece (2012) добавлены в список литературы как исходные работы, на которые опираются загруженные статьи. Работа Sattler (2025) используется осторожно: это магистерская диссертация, поэтому она не приравнивается к peer-reviewed статье, а рассматривается как современный методологический материал по neuro-adaptive architecture, HRV, CCT и ограничениям нейроархитектурных исследований.

В статье не используются неподтвержденные утверждения о том, что акустическая среда или проект Audiotheatre уже повышают эффективность стартапов, ускоряют принятие решений или формируют командную синхронизацию. Загруженная литература не предоставляет достаточных доказательств по этому вопросу. Поэтому такие связи формулируются только как исследовательские предположения для будущего эмпирического этапа.

2. Adaptive management: структурированное обучение в условиях неопределенности

Базовый вклад literature on adaptive management состоит в том, что управление неопределенностью понимается не как отказ от действия, а как необходимость действовать, одновременно производя знание. Истоки этой логики в загруженных работах связываются с Holling (1978), Walters (1986), Walters and Hilborn (1978), Walters and Holling (1990) и Lee (1993). Allen et al. (2011) описывают adaptive management как подход, основанный на признании неполноты знания и на включении обучения в сам управленческий процесс. Важным отличием от обычной пробы и ошибки является формальная структура: определение проблемы, постановка целей, выбор альтернатив, формулирование гипотез, мониторинг, оценка и корректировка решений (Allen et al., 2011).

Этот подход важен для исследования инновационных переходов только при осторожном переносе. Инновационный проект действительно может находиться в состоянии неопределенности, но это не означает, что любой гибкий стиль управления

автоматически является adaptive management. Для корректного применения этой логики будущий эмпирический дизайн должен содержать наблюдаемые индикаторы, заранее сформулированные гипотезы, механизм обратной связи и возможность корректировки действий на основе данных (Allen et al., 2011; Rist et al., 2012).

Критический обзор Rist et al. (2012) усиливает это требование. Авторы показывают, что термин adaptive management стал широко использоваться в научных статьях, policy documents и management plans, но его понимание и применение остаются неоднородными. В рассмотренном ими корпусе 187 работ только 8% фактически сообщали о внедрении adaptive management, а только 18% статей давали явное определение термина (Rist et al., 2012). Следовательно, для DBA-исследования важно не просто заявить «адаптивность», а определить, какие элементы адаптивного управления реально измеряются.

3. Пределы линейного цикла и значение сложности

Классическое представление adaptive management часто строится как цикл: оценка ситуации, проектирование действий, внедрение, мониторинг, интерпретация результатов и корректировка. Однако эмпирическая работа Fernández-Giménez et al. (2019) показывает, что в collaborative adaptive management этот цикл редко замыкается полностью. На основе четырех лет анализа meeting transcripts, stakeholder communications и biophysical monitoring data авторы показывают, что feedback loops между мониторингом и управленческими решениями остаются неполными из-за временных лагов, trade-offs, path-dependency и различий между типами знания участников (Fernández-Giménez et al., 2019).

Именно здесь возникает важное отличие от упрощенной управленческой логики. Сложность в CAM не является только помехой. Fernández-Giménez et al. (2019) показывают, что сложности и противоречия могут становиться условиями social learning: они создают disorienting dilemmas, которые заставляют участников пересматривать ментальные модели, отношения и представления о проблеме. Поэтому авторы предлагают рассматривать CAM не как круг, а как спираль, где прошлые решения, опыт и конфликты влияют на последующие возможности обучения (Fernández-Giménez et al., 2019).

Для инновационных переходов этот вывод имеет концептуальное значение. Переход от прототипа к рынку, от MVP к масштабированию или от творческой идеи к управленческой модели не должен описываться как линейная последовательность стадий. На основании CAM-литературы корректнее рассматривать его как эпизод повышенной неопределенности, где команда сталкивается с несовпадением целей, временными лагами данных, конфликтом экспертных языков и необходимостью коллективного пересмотра предположений. Однако это является авторским переносом CAM-логики в инновационный контекст и требует отдельной проверки.

4. Collaborative adaptive management как координация знания, интересов и решений

Scarlett (2013) определяет collaborative adaptive management через соединение трех элементов: науки, сотрудничества и ориентации на результат. Эта рамка возникает в условиях высокой неопределенности, сложности, взаимосвязанности проблем и постоянных изменений. В таких условиях управленческие решения становятся не только техническими, но и социальными: они затрагивают распределение ресурсов, роли экспертов, стейкхолдеров и лиц, принимающих решения (Scarlett, 2013).

Fernández-Giménez et al. (2019) развивают этот аргумент эмпирически, показывая, что CAM включает не только мониторинг и корректировку действий, но и knowledge coproduction, trust-building и multiple-loop social learning. Теоретически этот блок опирается на традиции social learning и organizational learning, связанные с Bandura (1977) и Argyris and Schön (1978). В рамках кейса Fernández-Giménez et al. (2019) разные stakeholder groups приносили различные типы знания и опыта; именно напряжение между этими

«социальными мирами» становилось источником обучения, но одновременно усложняло принятие решений.

Для инновационных команд этот блок литературы не является прямым доказательством эффективности CAM в стартапах. Его значение состоит в другом: он предоставляет аналитический язык для описания ситуаций, где founders, engineers, designers, investors, customers и managers могут по-разному понимать проблему, риск и успех. Если будущая DBA-работа будет использовать эту рамку, она должна показать эмпирически, какие именно типы конфликтов знания возникают в казахстанских инновационных проектах и как они связаны с обучением команды.

5. Adaptive governance и организационная чувствительность

Переход от CAM к adaptive governance расширяет масштаб анализа. Van Assche et al. (2022) рассматривают governance organizations как decision machines, которые участвуют в координации коллективно значимых решений, а communities — как социальную среду, относительно которой governance system ориентирует свои операции. С этой точки зрения организация стремится снижать сложность среды через решения, процедуры и рутины, но одновременно рискует стать менее чувствительной к тем условиям, от которых зависит ее устойчивость (Van Assche et al., 2022).

Ключевая идея adaptive governance в этой статье состоит в необходимости развивать sensitivity к изменяющейся социальной среде. Van Assche et al. (2022) подчеркивают, что разные типы организаций могут усиливать координационную способность governance system и стимулировать innovation to enable adaptation, но могут также замедлять реакцию на изменения и усложнять deliberation. Таким образом, организации одновременно выступают ресурсом и ограничением адаптации (Van Assche et al., 2022).

В применении к инновационным переходам этот подход позволяет избежать узкого понимания стартапа как набора задач и KPI. Инновационный проект является организационной конфигурацией, зависящей от внешних сигналов, ресурсов, стейкхолдеров и внутренних механизмов обучения. Но загруженные источники не содержат прямого эмпирического анализа стартапов Казахстана, поэтому данный вывод остается концептуальной интерпретацией.

6. Нейроархитектура и HRV: методологический мост, а не доказанный управленческий эффект

Для включения нейроархитектуры в управленческую рамку необходимо особенно строго разграничивать доказательства и предположения. Sattler (2025) описывает neuroarchitecture как междисциплинарное поле на стыке architecture and neuroscience, связанное с исследованием влияния built environment на brain, cognition, psychological well-being, behaviour and physiological responses. В этой работе также обсуждается allostatic load и использование biomarkers для оценки stress-related responses, включая HRV как показатель вариации интервалов между сердечными сокращениями и активности autonomic nervous system (Sattler, 2025).

Однако Sattler (2025) одновременно фиксирует важные ограничения. Во-первых, стрессовые реакции, наблюдаемые в neuroarchitectural research, не обязательно подтверждают allostatic overload. Во-вторых, интерпретация biomarkers осложняется межиндивидуальными различиями, временем суток, предшествующим стрессом и другими confounding variables. В-третьих, собственное пилотное исследование CCT and HRV в этой работе проводилось на малой выборке, что ограничивает generalizability результатов (Sattler, 2025).

Поэтому в настоящей статье HRV не рассматривается как универсальное доказательство эффективности среды. Он может быть включен только как потенциальный индикатор физиологической регуляции в будущей методологии. Для DBA-исследования это

означает, что нейроархитектура предоставляет язык и инструменты операционализации — stressor, biomarker, inter-individual variability, adaptive environment, Bayesian analysis — но не доказывает автоматически, что архитектурная или акустическая среда улучшает управленческие результаты.

7. Акустическая среда, фоносфера и границы доказательности

Акустическая экология, фоносфера и Audiotheatre в настоящей статье рассматриваются как элементы будущей нейро-адаптивной рамки для изучения внимания, стресса и командной синхронизации, но не как уже доказанные инструменты управления. Загруженная нейроархитектурная работа Sattler (2025) включает acoustic quality в область indoor environmental quality и отмечает, что unwanted noise exposure может иметь auditory and non-auditory consequences. В таблице обзора IEQ and biomarkers работа также фиксирует, что исследования звука и HRV дают неоднородные результаты: одни исследования не выявляют значимого эффекта sounds under different frequencies on HRV, другие указывают на возможные эффекты low frequency sound (Sattler, 2025).

Эта неоднородность особенно важна для корректности статьи. На основании загруженных источников нельзя утверждать, что акустическая среда прямо повышает когнитивную гибкость, командную синхронизацию или успешность инновационного перехода. Загруженная литература не предоставляет достаточных доказательств по этому вопросу. Следовательно, acoustic ecology и phonosphere должны быть представлены как перспективная область исследования, а не как доказанный управленческий инструмент.

Проект Audiotheatre в таком случае целесообразно позиционировать не как «эталонную» среду с уже доказанным эффектом, а как exploratory case для будущей эмпирической проверки. Это позволит сохранить научную новизну диссертации и одновременно избежать неподтвержденных causal claims.

8. Концептуальная рамка нейро-адаптивного управления инновационными переходами

На основе загруженной литературы нейро-адаптивное управление инновационными переходами можно определить как концептуальную исследовательскую рамку, объединяющую три уровня анализа. Первый уровень — adaptive management: структурированное обучение в условиях неопределенности через постановку целей, гипотез, мониторинг и корректировку (Allen et al., 2011; Rist et al., 2012). Второй уровень — collaborative adaptive management: совместное производство знания, работа с конфликтами и multiple-loop learning в сложных системах (Fernández-Giménez et al., 2019; Scarlett, 2013). Третий уровень — neuro-adaptive architecture: осторожное изучение того, как параметры среды могут быть связаны с физиологическими реакциями человека, включая HRV и другие biomarkers (Sattler, 2025).

В этой рамке инновационный переход понимается как ситуация, где команда должна одновременно принимать решения, обучаться, пересматривать ментальные модели и удерживать работоспособность в условиях неопределенности. Среда не объявляется причиной успеха. Она рассматривается как потенциальное условие, которое может поддерживать или затруднять когнитивную и физиологическую адаптацию участников. Данная связь требует эмпирической проверки, особенно в казахстанском контексте.

9. Статус доказательности ключевых утверждений

Для предотвращения недостоверных ссылок и чрезмерных обобщений в таблице 1 представлен статус основных утверждений статьи.

Утверждение	Статус	Основание	Как использовать в статье
Adaptive management является структурированным процессом обучения, а не обычной пробой и ошибкой.	Поддержано загруженной peer-reviewed литературой.	Allen et al. (2011); Rist et al. (2012).	Использовать как основу управленческой логики исследования.
Термин adaptive management часто используется неоднородно и требует строгой операционализации.	Поддержано загруженной peer-reviewed литературой.	Rist et al. (2012).	Использовать как аргумент против размытых формулировок.
CAM в реальности лучше описывать как спираль, а не как полностью замкнутый цикл.	Поддержано эмпирическим исследованием.	Fernández-Giménez et al. (2019).	Использовать как основу для анализа инновационных переходов как нелинейных процессов.
Adaptive governance требует организационной чувствительности к социальной среде.	Поддержано концептуальной academic literature.	Van Assche et al. (2022).	Использовать для организационного уровня анализа.
HRV может применяться как один из biomarkers физиологической регуляции.	Частично поддержано; требует осторожной интерпретации.	Sattler (2025).	Использовать только как методологический индикатор, не как доказательство эффективности.
Акустическая среда повышает результативность стартапов или командную синхронизацию.	Недостаточно доказательств.	В загруженной литературе прямых данных нет.	Формулировать только как гипотезу для будущего исследования.
Audiotheatre снижает стресс инновационных команд.	Недостаточно доказательств.	В загруженной литературе прямых данных нет.	Позиционировать как exploratory case, а не как подтвержденный инструмент.

10. Методологические следствия для дальнейшего DBA-исследования

Первое методологическое следствие состоит в необходимости разделять уровни анализа. Adaptive governance относится к организациям и их отношениям со средой; CAM — к коллективному обучению и координации разных типов знания; neuro-adaptive architecture — к индивидуальным физиологическим реакциям на параметры пространства. Эти уровни нельзя смешивать без операционализации переменных и без объяснения механизма связи между ними.

Второе следствие состоит в необходимости mixed-methods дизайна для будущего эмпирического DBA-этапа. Количественный этап может использовать опросные шкалы по восприятию адаптивности, когнитивной нагрузки, акустического комфорта и командного взаимодействия. Качественный этап может включать полуструктурированные интервью с founders, project managers и участниками инновационных команд. Однако включение HRV или других biomarkers потребует отдельного этического протокола, контроля confounding variables и пилотного тестирования (Sattler, 2025).

Третье следствие связано с будущим использованием Audiotheatre. На данном этапе корректная исследовательская формулировка должна звучать не как утверждение о доказанном эффекте, а как вопрос: может ли специально спроектированная акустическая и пространственная среда быть связана с изменением субъективной когнитивной нагрузки, ощущением командной синхронизации и отдельными физиологическими индикаторами стресса? Ответ на этот вопрос требует эмпирического дизайна, контрольной логики и осторожной интерпретации результатов.

11. Казахстанский контекст

Казахстанский контекст в настоящей статье является контекстом будущего эмпирического применения, а не уже доказанным объектом анализа. Для будущего DBA-этапа предполагается изучение инновационных проектов, акселераторов и управленческих команд в Казахстане; однако загруженная международная литература не содержит данных по казахстанским стартапам, корпоративным инновационным командам или проекту Audiotheatre.

Следовательно, все выводы, полученные из Allen et al. (2011), Rist et al. (2012), Fernández-Giménez et al. (2019), Scarlett (2013), Van Assche et al. (2022) и Sattler (2025), имеют общий теоретический или методологический статус. Казахстан-специфические выводы могут появиться только после проведения локального эмпирического этапа: интервью, анкетирования, кейс-анализа и, при необходимости, пилотного тестирования параметров среды.

12. Ограничения статьи

Первое ограничение состоит в том, что статья является концептуальной. Она не доказывает причинную связь между нейроархитектурной средой и результативностью инновационных команд. Второе ограничение связано с корпусом источников: основная peer-reviewed литература относится к natural resource management, environmental governance и adaptive governance, а не к стартапам или бизнес-акселераторам. Третье ограничение заключается в статусе источника по neuro-adaptive architecture: работа Sattler (2025) является магистерской диссертацией и используется как методологический ориентир, а не как окончательная доказательная база.

Четвертое ограничение касается акустической среды. Загруженные источники позволяют говорить о sound, noise, acoustic quality и отдельных biomarker-related findings, но не позволяют делать выводы о прямом влиянии акустической экологии на entrepreneurial outcomes. Пятое ограничение касается проекта Audiotheatre: в данной статье он может быть обозначен только как будущий exploratory case.

Заключение

Переработанный синтез показывает, что нейро-адаптивное управление инновационными переходами может быть сформулировано как перспективная концептуальная рамка DBA-исследования, но пока не как подтвержденная эмпирическая теория. Adaptive management дает структуру обучения в условиях неопределенности; collaborative adaptive management показывает, что сложность, конфликт знания и временные лаги могут не только мешать решениям, но и создавать условия для социального обучения; adaptive governance добавляет организационный уровень чувствительности к среде; neuro-adaptive architecture открывает возможность осторожного включения физиологических индикаторов в исследование условий принятия решений.

Основной исследовательский пробел состоит в отсутствии прямой доказательной связи между акустической или нейро-адаптивной средой и результативностью инновационных команд. Именно этот пробел может стать сильной основой диссертации: не утверждать заранее эффект Audiotheatre, а разработать методологию его проверки. Практическая значимость будущей работы будет зависеть от того, удастся ли эмпирически показать, какие параметры среды действительно связаны с когнитивной нагрузкой, субъективным состоянием команды, качеством взаимодействия и, возможно, физиологическими показателями стресса.

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Art History

МУЗЫКА НАЧИНАЕТСЯ С УЧИТЕЛЯ

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Аннотация. В статье рассматривается образ современного педагога-музыканта в системе дополнительного образования как личности, сочетающей высокий профессионализм, творческий потенциал, педагогическое мастерство и уважение к гуманистическим ценностям. Раскрывается роль педагога-музыканта в художественно-эстетическом, духовно-нравственном и личностном развитии ребенка. Особое внимание уделяется миссии учителя в формировании музыкальной культуры, раскрытии творческих способностей обучающихся, создании благоприятной образовательной среды и воспитании личности средствами музыкального искусства. Подчеркивается значимость дополнительного образования в современных условиях и определяются ключевые качества, характеризующие профессиональный портрет педагога-музыканта XXI века.

Ключевые слова: педагог дополнительного образования, педагог-музыкант, художественно-эстетическое воспитание, музыкальное искусство, профессиональное мастерство, творческое развитие, личность педагога.

Abstract. This article examines the image of the contemporary music teacher in the system of supplementary education as a professional who combines a high level of expertise, creative potential, pedagogical excellence, and a commitment to humanistic values. The study explores the role of the music teacher in the artistic, aesthetic, spiritual, moral, and personal development of children. Particular attention is given to the teacher's mission in fostering musical culture, developing students' creative abilities, creating a supportive educational environment, and nurturing the individual through the art of music. The article emphasizes the importance of supplementary education in contemporary society and identifies the key qualities that characterize the professional profile of the twenty-first-century music teacher.

Keywords: supplementary education teacher, music teacher, artistic and aesthetic education, musical art, professional excellence, creative development, teacher's personality.

Портрет современного педагога дополнительного образования – это образ человека, искренне преданного своему делу, воспринимающего профессию не просто как работу, а как жизненное призвание и важнейшую общественную миссию. Такой педагог убежден, что его труд имеет особую ценность, ведь именно он помогает раскрыть способности, таланты и творческий потенциал каждого ребенка.

Это педагог, который приходит в профессию по велению сердца и остается в ней по велению души. Его отличают высокий профессионализм, ответственность, любовь к детям, стремление к постоянному саморазвитию и готовность ежедневно вкладывать свои знания, опыт и душевное тепло в воспитание подрастающего поколения.

Особенно приятно осознавать, что необходимой составляющей этого собирательного образа педагога дополнительного образования являются педагоги-музыканты. Именно они открывают детям удивительный мир музыкального искусства, воспитывают художественный вкус, эмоциональную отзывчивость и духовную культуру, помогая каждому ученику найти собственный путь к прекрасному.

На протяжении всей истории человечества музыка была и остается неотъемлемой частью жизни «Homo sapiens» [1]. Она сопровождает человека с первых дней жизни, формирует его духовный мир, воспитывает чувство прекрасного и служит универсальным языком, понятным людям разных культур и поколений. Именно благодаря самоотверженному труду педагогов мир узнал выдающихся музыкантов – Дениса Мацуева, Михаила Плетнёва, Жанию Аубакирову, Хадиша Оналбаеву, Жанар Сулейманову и многих других. За каждым большим артистом стоит Учитель – наставник, который сумел разглядеть талант, поверить в него и помочь ему раскрыться.


Денис Мацуев


Михаил Плетнёв


Жания Аубакирова


Хадиша Оналбаева


Жанар Сулейманова

Перед нами, педагогами-музыкантами, всегда стояла и продолжает стоять особая миссия – открыть ребенку многогранный и поистине волшебный мир музыки. Наша задача заключается не только в том, чтобы научить играть на музыкальном инструменте или читать нотный текст, но и помочь услышать музыку сердцем, почувствовать ее красоту, глубину и силу эмоционального воздействия.

Увлекая своих учеников в этот процесс, мы вместе совершаем путешествие сквозь эпохи и музыкальные стили. Мы знакомимся с величавой красотой старинной музыки – сарабандой, паваной, гальярдой; открываем совершенство классических инвенций, сонат и этюдов; восхищаемся свободой импровизации и ритмическим богатством джаза.

Жанровое распределение учебного репертуара

Раздел репертуара	Жанры	Педагогическая направленность
Старинная музыка	Сарабанда, павана, гальярда	Формирование чувства стиля, освоение особенностей барочной и ренессансной музыки, развитие полифонического мышления и культуры звукоизвлечения
Классический репертуар	Инвенции, сонаты, этюды	Развитие технического мастерства, музыкального мышления, исполнительской культуры и навыков интерпретации произведений различных форм
Современная музыка	Джазовые пьесы	Развитие чувства ритма, синкопирования, свободы исполнительства, творческой инициативы и интереса к современным музыкальным стилям

Именно в этом многообразии музыкальных эпох и жанров рождается художественный вкус, формируется музыкальное мышление и воспитывается любовь к искусству, которая нередко остается с человеком на всю жизнь.

Портрет педагога-музыканта в системе дополнительного образования – это образ человека, который не только в совершенстве владеет музыкальным инструментом, но и находится в постоянном творческом поиске. Это педагог, умеющий мыслить, анализировать, вдохновлять и мотивировать своих учеников на новые достижения. Он не ограничивается передачей профессиональных знаний и исполнительских навыков, а помогает каждому ребенку раскрыть свои способности, поверить в собственные силы и почувствовать радость творческого самовыражения.

Настоящий педагог-музыкант – это наставник, психолог, воспитатель и единомышленник в одном лице. Он умеет найти индивидуальный подход к каждому ученику, поддержать в минуты сомнений, разделить радость первых успехов и научить достойно воспринимать временные неудачи. Именно поэтому его работа требует не только высокого профессионального мастерства, но и огромного терпения, душевной щедрости и искренней любви к детям.

Такой педагог готов трудиться «денно и нощно», вкладывая в своих воспитанников знания, силы и частицу собственной души, ведь самой высокой наградой для него становятся успехи учеников, их творческий рост и первые серьезные достижения на сцене. Именно в эти моменты приходит осознание того, что все усилия были не напрасны.

Несомненно, такой портрет невозможно заключить в жесткие рамки, ведь каждый педагог-музыкант уникален по своему внутреннему миру, профессиональному пути и творческой индивидуальности. Но при всем многообразии этих качеств неизменным остается одно: настоящий педагог-музыкант – это человек высокой культуры, обладающий широким кругозором, богатым духовным миром, тонким художественным вкусом и искренним стремлением не только обучать музыке, но и воспитывать через искусство личность, способную чувствовать, мыслить и творить.

Как не вспомнить слова А.П.Чехова: «В человеке всё должно быть прекрасно: и лицо, и одежда, и душа, и мысли…» [2]. Эти слова, сказанные более века назад, не утратили своей актуальности и сегодня, особенно когда речь идет о личности педагога. Именно учитель является тем человеком, с которого для ребенка начинается знакомство с миром знаний, искусства и духовных ценностей.

В современных реалиях, когда престиж профессии учителя заметно снизился, а требования общества к качеству образования, напротив, постоянно возрастают, особую значимость приобретает система дополнительного образования. Именно она становится тем образовательным пространством, где ребенок получает возможность раскрыть свои способности, развить творческий потенциал, сформировать устойчивый интерес к познанию и приобрести важнейшие личностные качества. Во многом именно дополнительное образование способно стать тем импульсом, который не только пробуждает любовь к искусству, но и способствует успешному освоению основ школьных наук, формируя мотивацию к дальнейшему обучению.

Ежегодно во всех учреждениях дополнительного образования проводятся вступительные прослушивания в детские музыкальные школы. Именно в этот день происходит первое знакомство ребенка и его родителей с педагогом-музыкантом. Нередко именно первое впечатление определяет эмоциональный настрой будущего ученика, его желание заниматься музыкой и доверие к своему наставнику. Поэтому улыбка, доброжелательный взгляд, спокойный и мягкий голос, искреннее внимание к каждому ребенку, атмосфера психологического комфорта и поддержка создают ощущение безопасности и уверенности в собственных силах. Такой «настрой на успех» помогает будущему ученику преодолеть естественные волнение, робость и смущение, а педагогу – увидеть не только уровень первоначальной музыкальной подготовки, но и творческий

потенциал, индивидуальные способности, эмоциональную отзывчивость и внутреннюю мотивацию ребенка.

«Искусство принадлежит народу» – именно этим жизнеутверждающим лозунгом мне хотелось бы завершить свое эссе. Искусство действительно принадлежит каждому, кто способен чувствовать, сопереживать, творить и открывать для себя красоту окружающего мира. Но путь к этому миру начинается с Учителя – мудрого наставника, вдохновляющего своим примером, открывающего перед ребенком удивительную вселенную музыки и помогающего ему поверить в собственные силы.

Быть педагогом-музыкантом – значит не только передавать знания и профессиональные навыки, но и воспитывать личность, формировать духовные ценности, развивать художественный вкус и любовь к прекрасному. Именно в этом заключается высокая миссия учителя, который своим трудом создает будущее культуры и общества.

Пусть в жизни каждого ребенка обязательно встретится такой Учитель, который сумеет зажечь искру творчества, а эта искра со временем превратится в яркий свет любви к искусству, знаниям и жизни.

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Biological Sciences

Development of Life Science Research in the Future: From Expanding Omics to Predictive, Integrative, and Causal Biology

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Abstract

Life science research is entering a phase in which biological discovery is no longer driven by a single dominant methodology, but by the convergence of many molecular, cellular, spatial, computational, and engineering approaches. The original omics revolution began with genomics and was rapidly expanded by transcriptomics, proteomics, metabolomics, and epigenomics. It has now matured into a broader ecosystem that includes single-cell omics, spatial omics, multi-omics integration, perturbation-driven profiling, organoid-based modeling, and artificial intelligence-assisted inference. Together, these developments are changing not only what can be measured, but also how biology is conceptualized. Instead of describing cells and tissues through static averages, the field is moving toward dynamic, mechanistic, and predictive frameworks that capture heterogeneity, context, and causality. This transition will influence basic biology, translational research, precision medicine, agriculture, environmental health, and bioengineering. At the same time, several less common or underused approaches, including glycomics, fluxomics, degradomics, exposomics, culturomics, and immunopeptidomics, are becoming increasingly important because they address dimensions of biology that remain incompletely explained by mainstream methods, yet their adoption has been slowed by technical difficulty, cost, poor standardization, and limited computational infrastructure (Cummings and Pierce, 2014; Winter and Krömer, 2013; Lagier et al., 2015; Xue et al., 2019; Savickas et al., 2020; Flender et al., 2025).

The next stage of life science research will likely be defined by seven interconnected shifts: wider use of single-cell and spatial measurements; routine multi-omic integration across time and scale; stronger coupling of perturbation with readout; greater use of organoids and organ-on-chip systems; adoption of biological foundation models; increased emphasis on rare, low-abundance, or environmentally driven signals; and a move from descriptive atlases toward actionable predictions. However, these opportunities are accompanied by major challenges. These include data quality problems, batch effects, the dominance of correlative over causal reasoning, unequal access to expensive platforms, reproducibility concerns, poor interoperability between datasets, underrepresentation of rare cell states and minority populations, ethical issues around data governance, and the risk that artificial intelligence may amplify rather than solve biological bias (Ma et al., 2020; Miao et al., 2021; Nam et al., 2024; Baek et al., 2025; Guo et al., 2025). This review examines the development of omics research, describes mainstream and underused omics fields,

predicts future directions, and discusses the problems, challenges, and advantages that are likely to shape the next era of life science.

Introduction

The history of modern life science can be described as a succession of expansions in biological resolution. Classical biology relied on morphology, physiology, and biochemistry. Molecular biology then allowed specific genes, transcripts, proteins, and pathways to be isolated and studied in detail. The rise of high-throughput technologies transformed that logic by enabling entire molecular layers to be measured simultaneously. Instead of asking how one gene behaves in one context, researchers began to ask how thousands of genes, transcripts, proteins, metabolites, or chromatin marks change together across development, disease, or environmental exposure. This was the central promise of omics. Omics methods created new scales of evidence, new statistical problems, and a new kind of biological thinking in which systems rather than isolated components became the primary unit of analysis (Veenstra, 2021).

At first, the intellectual momentum of omics came from abundance. More genes could be sequenced, more transcripts quantified, more proteins identified, and more metabolites profiled. Over time, however, the main limitation of this approach became clear. Large datasets did not automatically generate understanding. Bulk measurements often concealed heterogeneity. Molecular layers were measured separately, even though cells operate through simultaneous interactions among genome, epigenome, transcriptome, proteome, metabolome, and environment. The field became rich in associations but comparatively poor in mechanistic closure. In response, life science research began moving from bulk to single-cell analysis, from molecular inventories to spatially resolved systems, and from parallel datasets to integrative models that attempt to reconstruct regulation and function across scales (Ma et al., 2020; Vandereyken et al., 2023; Baysoy et al., 2023).

This transformation is not merely technical. It is conceptual. In earlier stages, genomics was often treated as the central layer, with the other omics fields viewed as secondary readouts. That hierarchy is no longer sustainable. The importance of epigenetic plasticity, post-transcriptional regulation, post-translational modification, metabolism, extracellular signaling, tissue organization, and environmental exposure has shown that no single molecular layer is sufficient to explain phenotype. Even genetic determinism has softened into a more relational view in which genotype sets possibilities but phenotype emerges from interactions among regulation, history, environment, and stochasticity. This has made multi-omics attractive, but it has also exposed the difficulty of integration. A truly mechanistic biology requires that multiple omics layers be linked in the same biological system, ideally in the same cell, over time, and within its spatial context (Miao et al., 2021; Liu et al., 2024).

Another important shift is the convergence of biology with engineering and computation. Microfluidics enabled high-throughput single-cell capture. Imaging innovations allowed transcriptomic and proteomic measurements to remain embedded in tissue architecture. CRISPR technologies created perturbation-based strategies for testing regulatory hypotheses at scale. Organoids and organ-on-chip systems provided experimental models that are more physiologically relevant than two-dimensional culture yet more controllable than whole organisms. Meanwhile, machine learning and foundation-model thinking are reshaping bioinformatics, particularly where the dimensionality and heterogeneity of biological data exceed traditional analytical frameworks (Deng et al., 2019; Kim et al., 2020; Wang et al., 2024; Guo et al., 2025).

Yet the future of life science research will not be defined only by popular or heavily funded methods. Some of the most important future advances may come from omics fields that remain relatively uncommon. Glycomics addresses glycans, which are crucial for immunity, signaling,

infection, and cell recognition, but are far harder to analyze than nucleic acids. Fluxomics captures metabolic flow rather than static abundance, and therefore addresses one of the most important missing dimensions in systems biology. Exposomics seeks to quantify lifetime environmental influence, a key driver of disease that genomics alone cannot explain. Culturomics restores the importance of microbial cultivation in an era dominated by sequencing. Degradomics reveals proteolytic processing events that standard proteomics often misses. Immunopeptidomics identifies antigenic peptides relevant to immunity and therapy but remains technically demanding. These approaches are less visible not because they are biologically marginal, but because they are analytically difficult, expensive, and not yet fully standardized (Cummings and Pierce, 2014; Winter and Krömer, 2013; Lagier et al., 2015; Savickas et al., 2020; Xue et al., 2019; Flender et al., 2025).

The central question, therefore, is not whether omics will continue to expand, but what kind of science this expansion will produce. Will future biology become truly predictive? Will integration produce causal understanding or simply more complex correlation? Which methods will become routine, and which will remain specialized? What are the next practical steps for research systems, laboratories, and institutions? And what difficulties and advantages should be expected as the field develops? These questions are especially relevant now because life science research stands between two phases: a descriptive phase that has generated extraordinary maps and datasets, and an emerging phase that aims to test, model, and intervene in living systems with greater precision. The development of life science research in the future will depend on whether omics can move from measurement alone to interpretation, from inventory to mechanism, and from data accumulation to biologically meaningful action.

Figure 1. From omics expansion to predictive, integrative, and causal biology

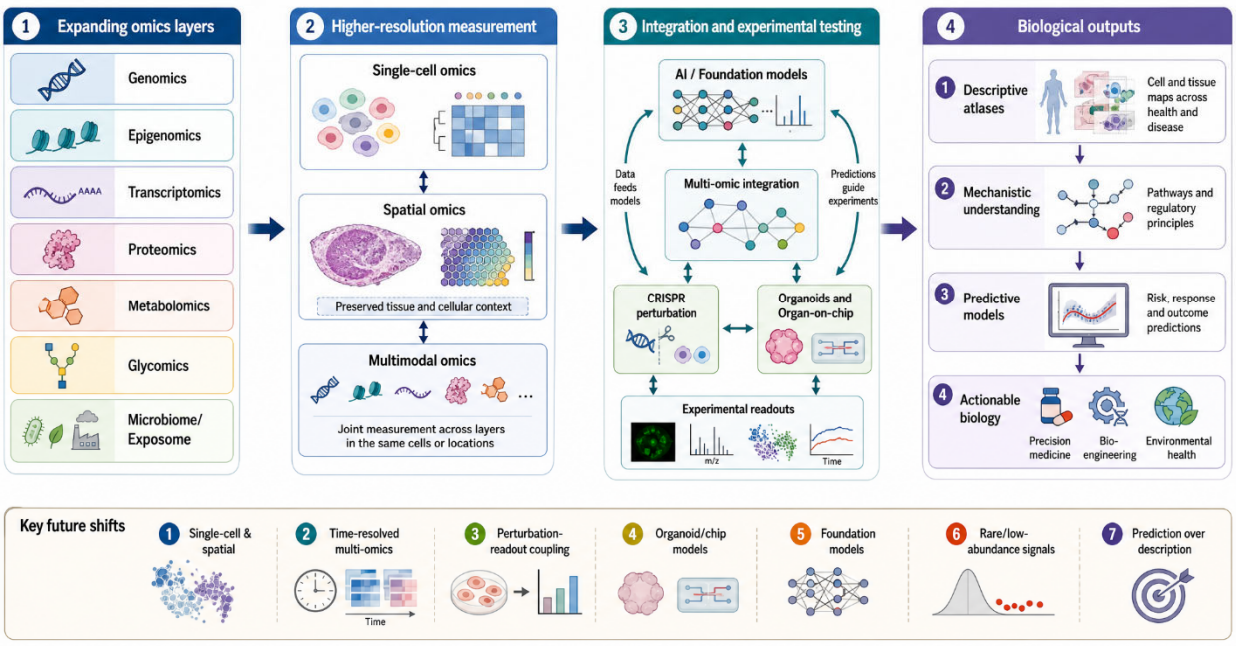

Figure 1. From omics expansion to predictive, integrative, and causal biology. Schematic overview of the evolving framework of life science research. The figure illustrates the progression from expanding molecular layers, including genomics, epigenomics, transcriptomics, proteomics, metabolomics, glycomics, and microbiome/exposome-related profiling, toward higher-resolution approaches such as single-cell, spatial, and multimodal omics. These measurement systems are increasingly linked to integrative computational analysis, foundation-model-assisted inference, perturbation-based testing, and physiologically relevant experimental platforms such as organoids and organ-on-chip models. Together, these advances support a transition from descriptive molecular atlases to mechanistic understanding, predictive modeling, and actionable biology across disease research, precision medicine, bioengineering, and

environmental health. The lower band highlights major future shifts expected to shape the field, including time-resolved multi-omics, perturbation-readout coupling, increased attention to rare or low-abundance signals, and a movement from description toward prediction and causality.

Evolution of the Omics Landscape

The first major omics wave was genomics, which introduced the idea that comprehensive molecular information could be obtained rather than sampled. Genome sequencing changed biology by establishing that complete molecular blueprints could be generated, compared, and interpreted. Beyond identifying genes, genomics opened the study of structural variation, noncoding regulation, evolutionary conservation, and population diversity. However, it also revealed a paradox. Knowing the genome was not the same as knowing how biology works. Many phenotypes are not directly inferable from DNA sequence alone because regulation is conditional, dynamic, and context dependent. As a result, genomics had to be complemented by transcriptomics, epigenomics, proteomics, and metabolomics.

Transcriptomics became especially influential because it provided a relatively accessible and scalable way to connect genotype with cell state. RNA sequencing made it possible to profile gene expression across tissues, disease states, developmental stages, and perturbations. For many years, transcriptomics was treated as a practical proxy for cellular identity and function. Yet that convenience also created distortions. Transcript abundance does not always predict protein abundance, protein localization, post-translational activity, or metabolic outcome. A transcriptomic cell atlas can be rich in categories but poor in mechanism. The same limitation applies to bulk epigenomics. Chromatin accessibility, DNA methylation, and histone modifications provide essential regulatory clues, but by themselves do not fully specify phenotype. Each omics layer clarifies one part of biological organization while leaving others unresolved (Veenstra, 2021).

The second major shift was toward systems biology. Omics was no longer interpreted simply as a set of parallel technologies but as the basis for integrated modeling. Systems biology promoted the view that biological function arises from networks, feedback loops, and multilevel interactions rather than linear pathways alone. This perspective increased interest in integrating proteomics and metabolomics with upstream molecular information. Proteomics brought researchers closer to functional machinery, including enzymes, receptors, complexes, and signaling effectors. Metabolomics added the small-molecule outputs that often reflect physiology more directly than transcripts. However, these layers were more difficult to standardize than nucleic-acid-based methods, and they required different instruments, sample preparation strategies, and statistical assumptions. As a result, the promise of whole-system integration advanced more slowly than the rhetoric surrounding it (Veenstra, 2021; Nam et al., 2024).

The third and perhaps most transformative shift has been the transition from bulk to single-cell biology. Bulk omics often averages across millions of cells, masking rare states, lineage intermediates, and context-specific regulatory programs. Single-cell methods exposed that apparent biological uniformity was frequently an artifact of measurement. Tumors, immune tissues, developing organs, and even healthy adult tissues contain extensive heterogeneity. Cell identity is better understood as a distribution of states than as a fixed label. Single-cell transcriptomics led this transition, but it quickly became clear that cellular heterogeneity cannot be understood from RNA alone. Single-cell epigenomics, single-cell proteomics, and multimodal methods emerged to address this need, and new studies began measuring paired modalities within the same cell, such as chromatin accessibility with gene expression or DNA methylation with transcriptome profiles (Deng et al., 2019; Ma et al., 2020; Vandereyken et al., 2023).

A fourth shift is now underway: the incorporation of spatial context. Single-cell dissociation techniques improved resolution but often destroyed the anatomical relationships that help explain

function. Cells do not act in isolation. They are embedded in tissues, niches, gradients, and local signaling environments. Spatial omics methods restore this information by measuring gene expression, protein abundance, or other molecular features while preserving tissue architecture. Spatial multi-omics goes further by combining several layers in situ. This is significant because spatial organization is not an accessory property of biology; in many cases it is biology. Development, immunity, neurobiology, fibrosis, regeneration, and cancer progression are all shaped by spatial arrangement and cell-cell interaction. The future of omics therefore lies not just in increasing molecular depth, but in linking depth to position and interaction (Liu et al., 2024; Vandereyken et al., 2023).

Finally, the omics landscape is expanding beyond canonical molecular layers. Researchers are increasingly interested in time, perturbation, environment, and function. Time-series omics seeks to capture trajectories rather than snapshots. Perturbation omics combines targeted intervention with high-dimensional readout to infer causality. Environmental and host-microbe omics extend molecular profiling into ecological and exposural space. Functional omics such as fluxomics, degradomics, and immunopeptidomics address aspects of living systems that are poorly captured by static abundance measurements. In this sense, the future of life science research is not a matter of adding endless new "-omics" labels. It is a matter of filling specific explanatory gaps left by earlier methods. The importance of a new omics field should therefore be judged by the biological dimension it captures, the question it answers, and the extent to which it can be integrated with complementary data.

Major Established Omics and Their Continuing Roles

Genomics will remain foundational because sequence information continues to anchor almost every other omics layer. Population genomics, clinical genomics, cancer genomics, and comparative genomics still generate essential insights into disease susceptibility, structural variation, gene regulation, and evolutionary innovation. In the future, genomics is likely to become more complete rather than less important. Long-read sequencing, pangenome frameworks, haplotype-resolved assembly, and improved structural variant detection will address limitations of short-read approaches and reference bias. This will be particularly important for understudied populations, repetitive genomic regions, immune loci, and complex disease architectures. However, genomics alone will increasingly be treated as necessary but insufficient. Its role will shift from being the main explanatory layer to being one coordinate within a broader multiscale framework.

Epigenomics will also continue to expand. DNA methylation, chromatin accessibility, nucleosome positioning, histone modifications, and three-dimensional chromatin interactions provide crucial information about regulatory potential and cellular memory. In development and disease, epigenomic states often explain why genetically similar cells behave differently. The next stage of epigenomics will likely involve greater temporal and single-cell resolution, stronger coupling to perturbation, and broader integration with lineage tracing. This matters because many processes of interest in future biology, such as cell-fate stability, reprogramming, aging, and treatment resistance, depend on persistent but reversible regulatory states rather than sequence change. A major challenge, however, is that epigenomic marks are easy to catalogue but harder to interpret causally. The field will need better frameworks for distinguishing regulatory consequence from regulatory cause.

Transcriptomics will remain the workhorse of many laboratories because of its accessibility, breadth, and interpretability. RNA-based profiling is still the fastest route to discovering state changes, classifying cell populations, and mapping responses to perturbation. Even as other modalities expand, transcriptomics will likely continue to serve as a common currency for

integration. Yet its future role will be more modest and more precise. Transcriptomics will no longer be assumed to stand in for total cellular function. Instead, it will be used as one informative layer among others, particularly when combined with epigenetic, spatial, proteomic, and phenotypic readouts. This shift is healthy. It corrects an earlier overreliance on mRNA abundance as a universal proxy.

Proteomics has long been viewed as the most direct route to functional biology because proteins execute most cellular processes. Nevertheless, proteomics historically lagged behind genomics and transcriptomics in throughput, sensitivity, and standardization. Advances in mass spectrometry, sample preparation, multiplexing, and computational analysis have greatly improved the field, but proteomics remains analytically demanding. Its future importance will be substantial because many key biological questions concern signaling, interaction, localization, processing, and post-translational modification, all of which are only incompletely captured by RNA. In precision medicine, drug development, immunology, and cell-state validation, proteomics is likely to become increasingly central. The most important change may be the growing integration of proteomics with other modalities rather than proteomics in isolation.

Metabolomics occupies a unique position because metabolites sit closest to phenotype in many contexts. They reflect nutrient use, redox balance, biosynthetic demand, stress response, microbiome interaction, and disease physiology. In future life science research, metabolomics is likely to gain importance in immunology, neuroscience, aging, cancer, microbiome science, and environmental health. Yet metabolomics also faces persistent obstacles: metabolite diversity is chemically vast, metabolite identities are not always easy to confirm, concentrations change rapidly, and metabolite abundance alone does not reveal pathway directionality. These limitations explain why metabolomics, while powerful, often needs to be interpreted together with fluxomics and proteomics.

Microbiome-related omics, including metagenomics, metatranscriptomics, metaproteomics, and metabolite profiling of host-microbe ecosystems, will remain a major growth area. Early microbiome research sometimes treated community composition as sufficient, but the field is gradually moving toward function, interaction, and causality. The future lies in understanding microbial activity, ecological resilience, host specificity, and the molecular mediators of microbe-host effects. This transition will require combining sequencing with cultivation, chemistry, imaging, and experimental perturbation. That is one reason why culturomics, although less common, may become increasingly important: sequencing alone cannot recover all functionally relevant members of a microbial community (Lagier et al., 2015).

Thus, the established omics fields will not disappear as new methods arise. Instead, they will be redistributed within a more integrated research architecture. The mature future of life science research will not be organized around which omics field is most fashionable, but around how specific omics layers can be combined to answer meaningful questions. Genomics may define possibility, epigenomics may define regulatory readiness, transcriptomics may describe immediate state, proteomics may reveal machinery, metabolomics may reveal physiological consequence, spatial omics may restore tissue logic, and specialized omics may fill critical blind spots. The development of future research will therefore depend less on inventing new categories and more on building coherent experimental systems in which multiple categories reinforce one another.

Single-Cell, Spatial, and Multimodal Omics

Among all current developments, single-cell and spatial omics are most likely to define the practical identity of near-future life science research. Their significance lies not only in resolution, but in a more realistic representation of biological organization. Traditional bulk measurements imply that tissues can be meaningfully summarized by average values. Single-cell profiling showed that this

assumption is often false. Rare cell states, transient developmental intermediates, exhausted immune subpopulations, therapy-resistant tumor clones, and microenvironment-specific responses can all be obscured by bulk averaging. This insight has altered how researchers think about development, disease, and treatment. Biology is increasingly understood as a structured distribution of states rather than a single consensus profile (Deng et al., 2019; Baysoy et al., 2023).
Single-cell multimodal methods extended this logic by measuring multiple molecular dimensions within the same cell. These methods are especially important because cell identity is not reducible to one layer. A cell may have a permissive chromatin landscape but low transcript output, or a strong transcriptional response with limited protein change, or an epigenetically primed state that only becomes functional after environmental stimulation. Methods that combine RNA with chromatin accessibility, DNA methylation, protein markers, or lineage information make it possible to infer regulatory relationships with greater confidence. They also help distinguish stable identity from temporary activation. Reviews in this area emphasize that the main advance of multimodal single-cell analysis is not simply more data, but more biologically coherent data because multiple layers originate from the same unit of observation (Ma et al., 2020; Vandereyken et al., 2023; Baysoy et al., 2023).
Yet single-cell technologies also create new problems. Data sparsity, dropout, dissociation bias, limited sensitivity for low-abundance molecules, and uneven modality coverage remain major obstacles. In many experimental settings, tissue dissociation changes the very biology being measured. Fragile cells may be lost, stress-response programs may be induced, and local context may be erased. These limitations explain why spatial omics has become so important. Spatial multi-omics preserves the anatomical location of cells and allows molecular information to be interpreted relative to neighbors, barriers, gradients, and niche structures. This is essential in tumor biology, developmental biology, immunology, and organ physiology, where function often depends as much on placement as on molecular identity (Liu et al., 2024).
Spatial multi-omics represents an especially strong candidate for future routine use because it addresses several shortcomings at once. It preserves context, supports the study of cellular interaction, and can bridge histology with molecular data. Importantly, it also changes the kind of questions researchers can ask. Instead of asking which genes are expressed, scientists can ask which cells communicate, which tissue zones become metabolically stressed, where drug resistance emerges, or how pathological remodeling spreads through an organ. According to current reviews, the long-term aim of spatial multi-omics is a form of molecular anatomy in which transcriptome, proteome, epigenome, genome, and metabolome can all be mapped onto tissue architecture with sufficient precision to reconstruct functional organization (Liu et al., 2024; Vandereyken et al., 2023).
Despite their power, these technologies are unlikely to become universally routine without substantial improvements. Current limitations include cost, high computational demand, incomplete molecular coverage, trade-offs between spatial resolution and throughput, short-read constraints, PCR bias, limited reagent availability for spatial proteomics, and still immature methods for spatial epigenomics (Liu et al., 2024). Moreover, the bioinformatic integration of high-dimensional single-cell and spatial datasets remains difficult. Multi-omic alignment can create elegant figures even when the underlying biological correspondence is weak. In the future, methodological rigor will need to increase alongside measurement sophistication. Better benchmarking, better error models, and more experimental validation will be required.
The next logical step is temporal and perturbational single-cell spatial multi-omics. A static atlas, however detailed, does not explain how a system changes. Future work will increasingly combine lineage tracing, serial sampling, CRISPR perturbation, and repeated spatial profiling to reconstruct trajectories and infer causality. This means that the field is moving from descriptive cell atlases toward dynamic tissue models. Such models may eventually support in silico prediction of

differentiation, disease progression, immune response, or treatment failure. If that occurs, single-cell and spatial multi-omics will become not just advanced readout tools, but central engines of mechanistic biology.

Rare or Underused Omics Methods and Why They Matter

A major weakness in many discussions of future life science research is the tendency to focus only on high-visibility technologies. However, some of the most biologically informative approaches remain underused. They matter precisely because they address what mainstream omics often misses.

Glycomics is a prime example. Glycans influence protein folding, trafficking, receptor interaction, immune recognition, pathogen attachment, and cell-cell communication. Despite this centrality, glycomics remains less widespread than genomics or transcriptomics. One reason is structural complexity. Unlike nucleic acids, glycans are branched, heterogeneous, and not directly templated in the same linear way. Their biosynthesis depends on enzyme networks, compartmentalization, substrate availability, and context-dependent processing. Analytical workflows are therefore technically demanding, and computational interpretation is less straightforward than sequence-based analysis. Cummings and Pierce argued that glycomics has enormous promise but lacks the broad reagent base, standardization, and routine accessibility that helped genomics scale earlier (Cummings and Pierce, 2014). Future research will likely integrate glycomics into immunology, oncology, infection biology, and precision medicine, but adoption will depend on better high-throughput workflows and more interpretable analytical platforms. The importance of glycomics in the future is not optional. It addresses a layer of biology that strongly shapes phenotype yet remains invisible to most standard omics pipelines (fig.2).

Figure 2. Integrative framework for predictive, integrative, and causal biology

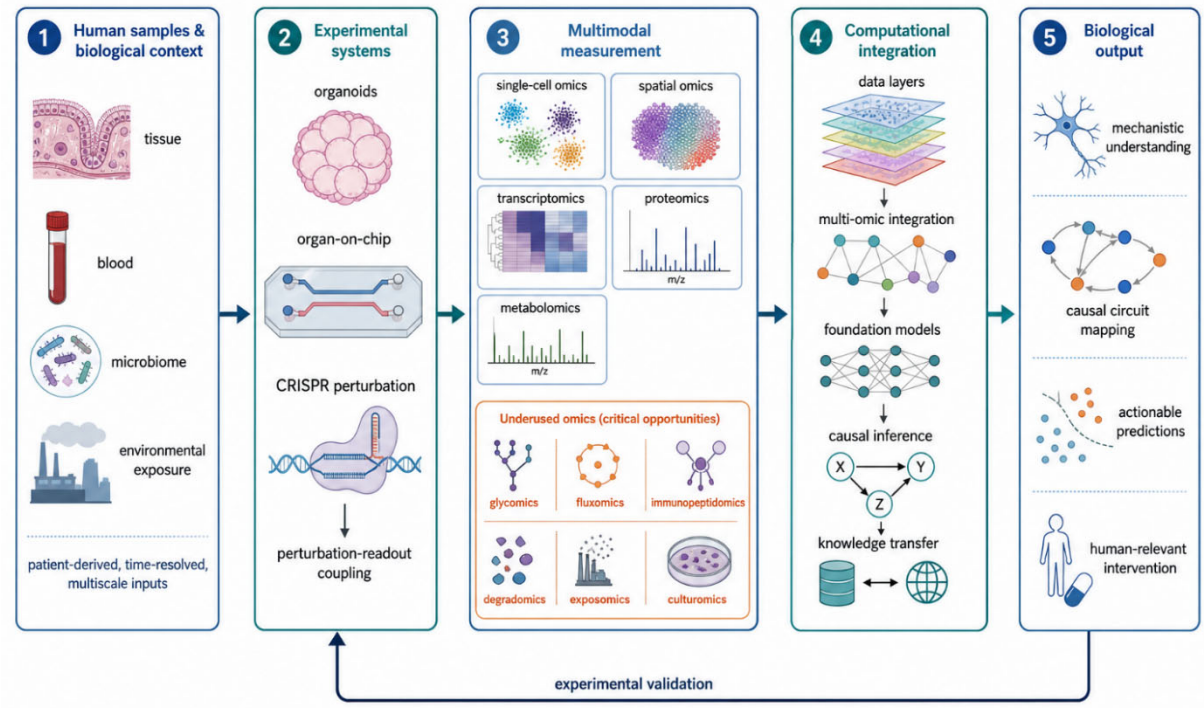

Figure 2. Integrative framework for predictive, integrative, and causal biology. Schematic overview of a closed-loop life science research pipeline linking human biological

context, experimental model systems, multimodal molecular measurement, computational integration, and biologically actionable output. Human-derived and environmentally informed inputs feed into organoid-, organ-on-chip-, and perturbation-based systems, enabling coupled experimental manipulation and readout. These systems are profiled through mainstream and emerging omics layers, including single-cell and spatial omics as well as glycomics, fluxomics, immunopeptidomics, degradomics, exposomics, and culturomics. Integrated data are then assimilated through multi-omic modeling, foundation-model-based inference, and causal analysis to generate mechanistic understanding, circuit-level interpretation, and actionable predictions. A feedback loop from prediction to experimental validation highlights the transition from descriptive atlas-building to iterative, testable, and human-relevant causal biology.

Fluxomics is another underused but potentially transformative field. Standard metabolomics measures the abundance of metabolites, but abundance does not necessarily reveal pathway activity. Two cells may have similar metabolite levels yet radically different metabolic fluxes because production and consumption rates differ. Fluxomics, often using isotope tracing and computational modeling, attempts to quantify the movement of material through pathways. This is especially important in cancer metabolism, microbial engineering, stem-cell fate, immune activation, and stress physiology. Winter and Krömer described fluxomics as a bridge between molecular data and phenotype because it captures functional biochemical throughput rather than static pools (Winter and Krömer, 2013). It remains relatively uncommon because experiments are laborious, data interpretation requires specialized expertise, and integrating isotopic, enzymatic, and modeling information is not easy. Nevertheless, if life science research truly aims to become mechanistic, fluxomics is likely to gain importance. Many future therapeutic and engineering questions will depend less on whether a metabolite is present than on where it is going and how fast.

Exposomics addresses another large blind spot. A substantial proportion of disease risk and biological variability is influenced by non-genetic exposures, including diet, pollutants, drugs, stress, infection, social environment, and climate-associated factors. Genomics explains only part of health variance. Exposomics aims to quantify the totality, or at least a much broader fraction, of environmental influence across the life course. Its difficulty lies in the sheer heterogeneity, temporal variability, and low-abundance nature of many exposures. No single analytical platform can capture all relevant chemicals or environmental signatures, and computational feature alignment remains a major challenge (Xue et al., 2019). More recent perspectives suggest that exposomics will become increasingly central to public health, environmental medicine, and systems epidemiology because it offers a route to connect environment with molecular mechanism and disease trajectory (Gago-Ferrero et al., 2025). As climate change, urbanization, and chemical complexity intensify, the importance of exposomics is likely to grow dramatically.

Culturomics is underused for a different reason. In the age of sequencing, culture was sometimes seen as old-fashioned or unnecessary. Yet sequencing-based microbiome analysis has its own biases and often misses low-abundance or hard-to-detect organisms. Lagier and colleagues showed that culturomics can uncover microbial “dark matter” that metagenomics alone may overlook, while also enabling direct functional characterization of isolated organisms (Lagier et al., 2015). The problem is that culturomics is labor-intensive, costly, and operationally heavy. It requires many culture conditions, significant workforce, and extensive downstream identification. Even so, its complementarity to sequencing makes it increasingly valuable. Future microbiome science, especially for translational or mechanistic goals, will likely require a reintegration of cultivation with multi-omics rather than a choice between them.

Degradomics examines proteolytic processing and cleavage events. This is critical because protein function is often altered not only by abundance but by protease-mediated activation, inactivation,

truncation, release, or localization change. Standard proteomics may miss these events or fail to interpret them functionally. Savickas and colleagues emphasized that degradomics provides mechanistic insight into protease biology and substrate processing, but adoption has been limited by technical sensitivity requirements, targeted workflow complexity, and the need for specialized analytical pipelines (Savickas et al., 2020). In future life science research, degradomics may become increasingly important in inflammation, fibrosis, neurodegeneration, cancer invasion, and extracellular matrix biology.

Immunopeptidomics is another rare but strategically important approach. It identifies peptides presented by major histocompatibility complexes, making it directly relevant to antigen discovery, cancer immunotherapy, infectious disease, vaccine development, and autoimmunity. Its relatively limited use reflects the difficulty of isolating low-abundance peptide repertoires, interpreting post-translationally modified antigens, and building reliable bioinformatic pipelines. Recent reviews emphasize that immunopeptidomics sits at the intersection of proteomics, immunology, and precision therapy, and that its growth may accelerate as mass spectrometry and artificial intelligence improve (Flender et al., 2025). The field is not obscure because it lacks value, but because it imposes a high technical threshold.

These uncommon omics fields reveal an important principle for future biology. What is rare in method adoption is not necessarily rare in biological importance. The methods that remain uncommon often do so because they target difficult molecules, dynamic processes, low-abundance signals, or context-heavy interpretations. Yet these are precisely the dimensions most needed for a mature, mechanistic science. Therefore, the future development of life science research should not prioritize only scalable and fashionable omics, but also invest in difficult omics that close explanatory gaps.

Computational and AI-Driven Biology

As life science research becomes more multi-omic and multi-scale, computation is no longer a support activity; it is a defining layer of the research process. Early bioinformatics mainly handled storage, alignment, annotation, and differential analysis. The current stage is very different. Researchers now expect computational models to integrate modalities, identify latent structure, predict perturbation outcomes, transfer annotations across datasets, and assist in the interpretation of complex biological states. In this sense, the future of biology is inseparable from the future of modeling.

One of the strongest trends is the rise of multimodal integration frameworks. These methods attempt to align transcriptomic, epigenomic, proteomic, and spatial information, often by learning shared latent spaces. Ma and colleagues summarized the practical challenges of single-cell multi-omics integration, including data sparsity, modality imbalance, missing values, and the risk of forcing biologically nonequivalent data into mathematically convenient structures (Ma et al., 2020). This warning remains crucial. Integration is not automatically insight. Future progress will depend on preserving biological meaning while using computational abstraction.

Artificial intelligence has become especially attractive because many biological datasets now exceed the assumptions of classical statistics. Reviews on multimodal omics integration describe machine learning as a potential bridge across highly heterogeneous data types and a key component of precision medicine workflows (Nam et al., 2024). Foundation-model thinking extends this ambition further. Large pretrained models may learn reusable biological representations from massive corpora of sequences, single-cell profiles, structures, or multimodal data. Guo and colleagues argue that foundation models in bioinformatics could support tasks ranging from representation learning to multitask prediction and biological knowledge transfer (Guo et al., 2025). In single-cell biology, these ideas are becoming particularly influential.

Single-cell foundation models are often presented as “virtual cells” or general biological learners that can support annotation, integration, imputation, perturbation prediction, and hypothesis generation (Baek et al., 2025). This is a compelling vision because it suggests that some biological regularities can be learned at scale and reused across tasks. If successful, such models could lower barriers for small laboratories, standardize parts of analysis, and accelerate discovery from increasingly complex datasets. They may also help integrate modalities that are otherwise difficult to compare directly.

However, the limitations are serious. Reviews emphasize that foundation models are only as good as their training corpora. Public biological data contain technical noise, batch effects, duplicated entries, class imbalance, and uneven representation of tissues, species, populations, and disease states (Baek et al., 2025; Guo et al., 2025). Rare cell types, unusual experimental conditions, and underrepresented populations may be poorly modeled. Attention weights and embeddings can look interpretable without being biologically causal. Large models are computationally expensive, and the field still lacks unified benchmarking standards. There is also a cultural risk: biology may become too dependent on compressed representations that are analytically elegant but experimentally undervalidated.

Thus, the next steps in computational life science research should be ambitious but disciplined. AI should be used not to replace mechanism, but to prioritize hypotheses, integrate evidence, and design better experiments. The best future models will probably be hybrid systems that combine large-scale learning with explicit biological constraints, knowledge graphs, kinetic information, and perturbation data. In other words, future computational biology should become more biological, not merely more computational.

Experimental Models for the Next Phase of Omics Research

Omics technologies have become so powerful that traditional model systems are increasingly their limiting factor. A transcriptome or proteome is only as informative as the biological system from which it is derived. That is why organoids, organoids-on-chips, perturbation platforms, and engineered cellular systems are becoming essential components of future life science research.

Organoids provide multicellular, three-dimensional, self-organizing systems that capture aspects of tissue architecture and developmental logic. Kim and colleagues described organoids as valuable models for human biology and medicine because they can bridge the gap between oversimplified cell culture and imperfect animal models (Kim et al., 2020). More recent reviews highlight their growing integration with single-cell and multi-omics analyses, which allows organoids to be characterized not just morphologically but molecularly and functionally across developmental and disease contexts (Han et al., 2024). The major future importance of organoids is that they allow mechanistic hypotheses generated by omics data to be tested in systems that retain more realism than flat monolayer cultures.

Organoids-on-chips extend this logic by adding controlled microenvironments, fluid dynamics, gradient formation, real-time monitoring, and sometimes inter-organ communication. Wang and colleagues emphasize that these systems can improve physiological relevance, support dynamic observation, model chronic disease more effectively, and reduce reliance on animal systems (Wang et al., 2024). This is particularly important for drug screening, toxicology, developmental biology, and translational medicine. However, major bottlenecks remain, including lack of standardization, material constraints such as small-molecule absorption by device materials, difficulty in co-culturing multiple organoid types long term, and limited phenotype mapping frameworks (Wang et al., 2024).

The next phase of life science research will likely combine organoid systems with spatial omics, perturbation readouts, and AI-assisted analysis. This combination may enable a new experimental

paradigm: building a human-relevant model, perturbing it at scale, reading out multiple molecular layers, and using computational models to infer intervention points. Such workflows could transform cancer biology, developmental disease modeling, infectious disease, and regenerative medicine.

CRISPR-based perturbation platforms will also be central. One of the biggest weaknesses of current omics is that much of it remains descriptive. Perturbation-based designs allow causal testing by linking gene or regulatory disruption to transcriptomic, epigenomic, or phenotypic outcome. When combined with single-cell readouts, such approaches move the field beyond atlas-building into causal circuit mapping. The future of life science research is therefore likely to depend not just on better measurement, but on experimental systems that let researchers test what the measurements mean.

Predictions for the Future Development of Life Science Research

The future of life science research will likely unfold through several interconnected developments. First, multi-omics will become more targeted and biologically strategic. Instead of measuring every possible layer in every experiment, researchers will increasingly choose combinations that best answer specific questions. This will improve experimental design and reduce the “collect everything first, understand later” tendency that has characterized some omics work.

Second, single-cell and spatial technologies will become more routine, but also more modular. Laboratories may not always perform full-scale spatial multi-omics, yet many will use at least one spatially informed assay or one multimodal single-cell strategy. The distinction between sequencing-based and imaging-based analysis may also blur. Future tissue biology will likely integrate histology, molecular readout, and computational reconstruction into unified workflows.

Third, temporal biology will become far more important. Static omics snapshots have dominated because they are easier to obtain, but the most important biological processes are dynamic. Future studies will increasingly measure state transitions, lineage histories, and treatment responses over time. This will be especially important in embryology, immunology, neurobiology, wound repair, aging, and cancer evolution (figure 3).

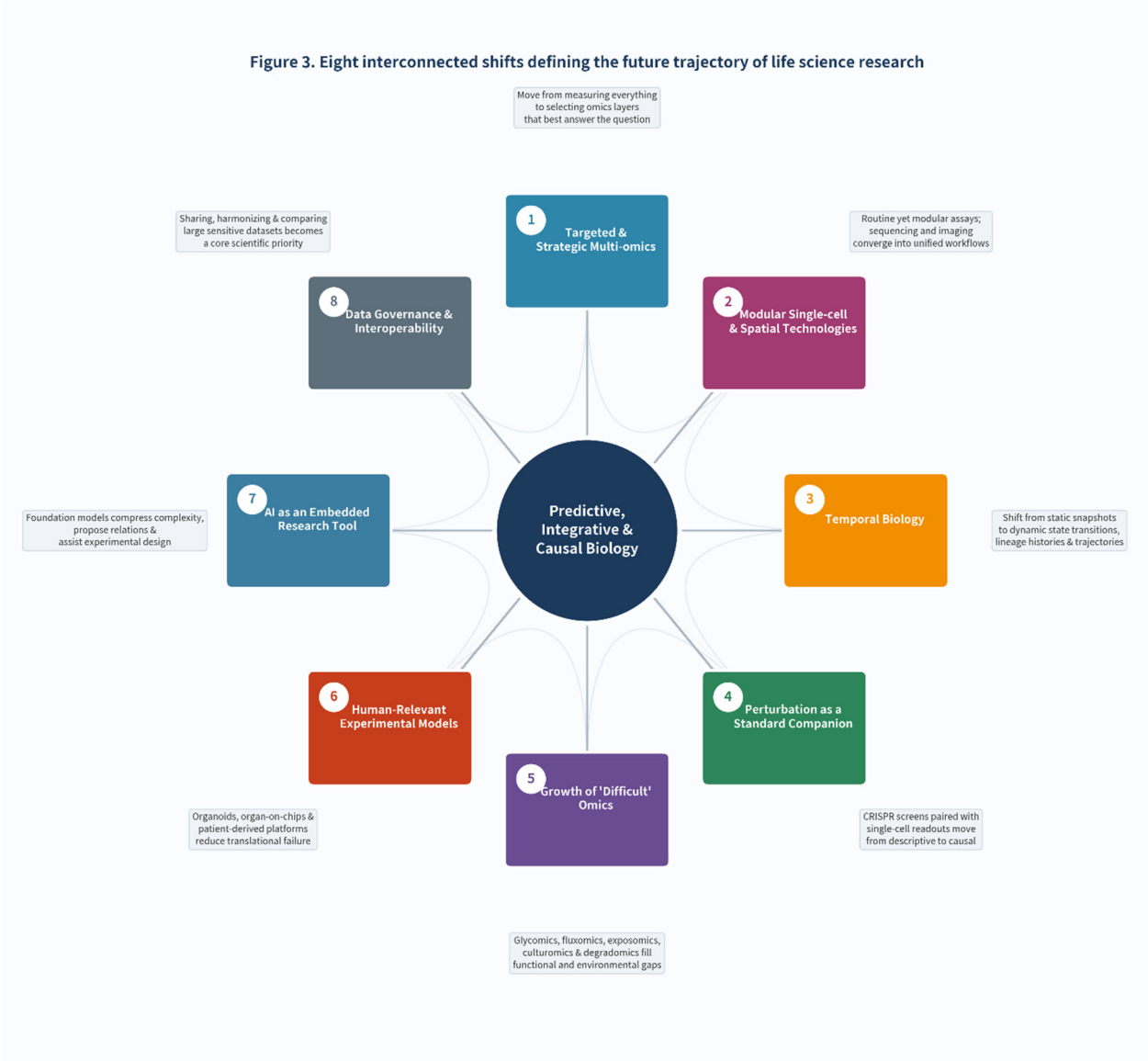

Figure 3. Temporal biology as a central framework for future life science research. Schematic illustration of the shift from static omics snapshots toward dynamic, time-resolved analysis of biological systems. The figure highlights how future studies will increasingly capture state transitions, lineage histories, and treatment responses over time, enabling a more predictive and mechanistic understanding of biological processes. This temporal framework is expected to be particularly important in embryology, immunology, neurobiology, wound repair, aging, and cancer evolution, where cellular and molecular changes unfold across defined trajectories rather than fixed end points. Together, these approaches will support the transition from descriptive biology to integrative and causal models of biological function and disease progression.

Fourth, perturbation will become a standard companion to profiling. Observational omics will remain useful, but it will be insufficient for causal discovery. The most influential future studies are likely to combine perturbation libraries, single-cell readouts, spatial context, and functional validation. This will make biology less descriptive and more intervention-ready.

Fifth, difficult omics will grow in importance. Glycomics, fluxomics, degradomics, exposomics, culturomics, and immunopeptidomics are likely to become more visible because the dominant omics fields cannot fully answer questions about functional regulation, environmental influence, proteolytic control, antigen presentation, or microbial cultivability. Their growth may be slower than that of transcriptomics, but their importance per experiment may be high.

Sixth, human-relevant experimental models will expand. Organoids, microphysiological systems, and patient-derived platforms will increasingly be used as testing grounds for mechanistic hypotheses generated from omics datasets. This shift may reduce some translational failures caused by oversimplified models or species differences.
Seventh, artificial intelligence will become deeply embedded in life science research, but probably not as an autonomous discoverer. Its more realistic role will be to compress complexity, propose relationships, assist design, identify patterns, and support cross-dataset inference. The most successful biological AI systems will likely be those that remain tightly connected to experimental validation and mechanistic reasoning (Nam et al., 2024; Baek et al., 2025; Guo et al., 2025).
Eighth, data governance and interoperability will become central scientific issues rather than administrative details. As datasets grow larger and more sensitive, the ability to share, harmonize, and compare data across institutions will directly affect discovery speed and reproducibility. The future research ecosystem will reward not just technological novelty, but infrastructure quality.
Overall, the future development of life science research can be summarized as a transition from broad molecular cataloguing to predictive, spatially aware, perturbation-informed, and experimentally testable systems biology.

Difficulties, Challenges, and Problems We Should Expect

The first major challenge is technical fragmentation. Different omics layers still require different sample handling protocols, instruments, quality-control pipelines, and analytical assumptions. This makes true integration difficult. Even when multiple omics layers are available, they may not be measured in the same cells, same tissues, same times, or same physiological states. As a result, “integration” may sometimes reflect computational convenience more than biological coherence (Ma et al., 2020; Miao et al., 2021).
Second, data quality will remain a limiting problem. Single-cell data are sparse, noisy, and batch sensitive. Spatial methods can be expensive and imperfect in resolution. Proteomics and metabolomics suffer from identification and quantification challenges. Rare omics fields often face even greater issues, such as low signal abundance, unstable analytes, lack of standards, or limited reference databases. More data will not automatically solve these problems. In some cases, it may amplify them.
Third, cost inequality will shape the field. The most advanced platforms are expensive. Laboratories in well-funded centers may generate multimodal spatial datasets integrated with organoid screens and AI pipelines, while others remain limited to simpler assays. This creates a stratified scientific ecosystem. If future biology becomes too dependent on expensive platforms, it risks narrowing participation and concentrating innovation.
Fourth, interpretability will remain difficult. High-dimensional data often produce clusters, embeddings, trajectories, and networks that are visually persuasive but biologically uncertain. AI models can intensify this issue if predictions become more opaque. There is a risk that future life science research may become rich in computational representation but poor in experimentally grounded explanation.
Fifth, rare and unusual biology may remain underdetected. Foundation models and atlases tend to perform best on abundant, well-represented states. Rare cell types, minority microbial populations, uncommon disease variants, and underrepresented human populations may continue to be poorly characterized. This is not only a technical issue but a scientific justice issue because the future benefits of precision biology could be distributed unequally.
Sixth, reproducibility will continue to be challenging. Complex multi-step workflows increase opportunities for hidden variability. Differences in dissociation, antibody quality, isotope labeling, matrix effects, spatial segmentation, or computational preprocessing can alter results substantially.

Future progress will therefore depend on community standards, benchmarking consortia, metadata discipline, and open validation culture.

Seventh, causality will remain difficult. Even with more data and better models, many omics studies may still yield association rather than mechanism. This is particularly true when experiments are cross-sectional and observational. Future biology must resist the temptation to treat integrative correlation as causal truth. Perturbation, longitudinal sampling, and orthogonal validation will be essential.

Eighth, ethical and governance problems will grow. Human multi-omics data can be deeply identifying and clinically sensitive. Spatial tissue maps, longitudinal exposures, and integrated health records raise privacy concerns. AI models trained on such data may inherit hidden biases or create unfair predictive systems. International differences in regulation may complicate collaboration.

Ninth, environmental and sustainability issues should not be ignored. Large-scale omics and AI pipelines consume reagents, energy, storage, and computational infrastructure. As life science research scales up, sustainability will become a practical and ethical consideration.

Finally, there is a conceptual challenge. The field must avoid mistaking comprehensiveness for understanding. A future in which every molecule is measured but few mechanisms are tested would not represent scientific maturity. The development of life science research should therefore be judged not by the amount of data produced, but by the clarity of the biological questions answered.

Advantages and Opportunities We Should Expect

Despite these difficulties, the advantages of future omics-driven research are profound. First, biological resolution will continue to improve. Researchers will be able to study not only which molecules are present, but where they are, in which cells, under which conditions, and with what functional consequences. This level of detail will transform developmental biology, pathology, immunology, neuroscience, and regenerative medicine.

Second, medicine is likely to become more precise and more mechanistic. Multi-omics approaches may improve patient stratification, biomarker discovery, target prioritization, and treatment monitoring. Spatial and single-cell methods may clarify why some therapies fail, where resistance emerges, and how microenvironments shape outcome.

Third, underused omics fields may reveal dimensions of disease and physiology that have long remained hidden. Glycomics may improve understanding of immunity and cell recognition. Fluxomics may identify metabolic liabilities. Exposomics may explain non-genetic disease drivers. Immunopeptidomics may strengthen vaccine and immunotherapy pipelines. Degradomics may reveal protease-regulated disease mechanisms. Culturomics may recover functionally important organisms missed by sequencing.

Fourth, future biology will become more experimentally testable. Organoids, perturbation screens, and high-content multi-omic readouts will allow hypotheses to be tested in increasingly realistic systems. This will reduce the gap between descriptive biology and intervention.

Fifth, better integration may improve theory itself. Biology may move toward more coherent models of how regulation, environment, metabolism, spatial context, and history combine to generate phenotype. In that sense, the real advantage of future omics is not only technical power, but the chance to build a more complete explanatory science.

Conclusion

The future of life science research will be shaped by the continued expansion of omics, but even more by the way those omics are integrated, interpreted, and tested. The field is moving beyond a phase in which success was defined mainly by the ability to generate large molecular datasets. The next phase will reward spatial awareness, temporal resolution, perturbational logic, functional modeling, and computational systems that remain tied to experimental validation. Classical omics fields such as genomics, transcriptomics, proteomics, metabolomics, and epigenomics will remain indispensable, but they will increasingly operate within broader multi-omic and model-based frameworks. Single-cell and spatial omics are likely to become central pillars of routine research, while less common methods such as glycomics, fluxomics, exposomics, culturomics, degradomics, and immunopeptidomics will become more important as researchers confront biological questions that cannot be answered by mainstream methods alone.

The next steps in scientific research should therefore include deeper investment in integrated experimental design, stronger support for difficult but informative omics fields, improved computational rigor, better human-relevant model systems, wider perturbation-based validation, and more equitable data infrastructure. The difficulties ahead are real: cost, noise, interpretability, bias, reproducibility, ethical complexity, and the persistent challenge of causality. Yet the advantages are greater. If these challenges are managed carefully, future life science research will become more predictive, more mechanistic, more human-relevant, and more capable of explaining how living systems truly work.

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