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Integrating mathematical analysis and biotechnological approaches for enhanced environmental management

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ABSTRACT

As environmental challenges continue to escalate, the need for innovative and effective solutions is paramount. This paper presents a comprehensive study at the intersection of biotechnology and mathematical analysis, aiming to address environmental management issues with a novel and integrated approach. Our research focuses on the development of cutting-edge strategies that harness the power of biotechnology while employing mathematical modelling and analysis for optimization and prediction. The novelty of our work lies in its interdisciplinary nature, bridging the gap between biotechnology and mathematics to tackle complex environmental problems. We begin by examining bioremediation techniques, particularly the use of microorganisms, to remediate contaminated sites. Mathematical models allow for the optimization of bioremediation processes, enabling faster and more cost-effective cleanup of polluted sites. In the realm of wastewater treatment, our study incorporates biotechnological advancements for optimal pollutant removal and resource recovery. Furthermore, we explore the potential of genetically modified organisms (GMOs) in environmental management, demonstrating the power of combining biotechnology with mathematical analysis to develop tailored solutions for environmental challenges. This paper highlights the synergistic relationship between biotechnology and mathematical analysis in the context of environmental management. Our research not only provides novel insights into the optimization and prediction of biotechnological processes but also offers sustainable solutions for environmental remediation and conservation. Our study presents promising numerical results, indicating substantial enhancements in pollutant removal efficiency, resource recovery, and the overall sustainability of environmental management. These findings demonstrate the transformative potential of our integrated approach, providing tangible evidence of its real-world impact on environmental challenges.

Keywords: Bioremediation, Biotechnology, Environmental management, Mathematical analysis, Modeling, Sustainability, Vermicompost.
Article type: Research Article.

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INTRODUCTION

Environmental challenges continue to be among the most pressing global issues of our time (Elkhlifi *et al.* 2023). The accelerating pace of climate change, the degradation of ecosystems, the proliferation of pollutants, and the depletion of natural resources are compelling reminders of the urgent need for innovative and effective solutions. In the face of these challenges, the integration of biotechnology and mathematical analysis emerges as a beacon of hope - a promising avenue for achieving enhanced environmental management (Azizi & Nejatian 2022). The significance of this topic lies in its potential to address the complex and multifaceted nature of environmental problems (Tills *et al.* 2023). Environmental management is no longer confined to the traditional methods of the past. Instead, it necessitates an interdisciplinary approach that harnesses the power of biotechnology to develop novel strategies and mathematical analysis to optimize, predict, and guide these strategies. This innovative fusion of disciplines has the potential to revolutionize the way we approach environmental issues (Bresciani *et al.* 2023). The need for such innovation is underscored by the fact that conventional approaches are often limited in their scope, efficiency, and sustainability. By juxtaposing the molecular intricacies of biotechnology with the analytical precision of mathematical models, we can uncover previously uncharted paths to cleaner ecosystems, more efficient resource management, and a sustainable future for generations to come (Magdy *et al.* 2023). Environmental challenges pose a persistent and escalating threat to the delicate balance of our planet's ecosystems (Alam & Azalie 2023). The 21st century has ushered in an era marked by growing concerns over climate change, biodiversity loss, pollution, and resource depletion (Azizi *et al.* 2021; Ghorbanzadeh *et al.* 2019; Saeidi *et al.* 2023). Addressing these challenges requires not only a profound reevaluation of our practices but also the harnessing of innovative tools and strategies that align with the principles of sustainability and conservation. At the forefront of this transformative endeavor stands the pivotal role of biotechnology, offering a beacon of hope in the face of these intricate and interconnected environmental dilemmas. The environmental challenges we confront today are multifaceted and, in many cases, global in scope. Climate change, primarily driven by anthropogenic factors, has set in motion a chain reaction of consequences, from rising temperatures and sea levels to more frequent and severe weather events. Ecosystems, the Earth's life-support systems, are under increasing stress, resulting in the loss of biodiversity and fragile ecological balances. Pollution, whether in the form of air pollutants, plastics in our oceans, or contaminants in our soils, undermines both human and environmental health. Meanwhile, the unsustainable extraction of natural resources places immense pressure on our planet's finite reserves (Abad *et al.* 2023; Semin *et al.* 2023). To tackle these multifarious challenges, the conventional view of nature as a self-regulating system is being reimagined (Stradella & Palmerini 2013). Instead, the integration of biotechnology, the science of manipulating living organisms or their components, emerges as a promising avenue. Biotechnology equips us with the means to design, engineer, and optimize biological processes and systems to address these challenges in novel and effective ways (Yeginbay *et al.* 2022). It empowers us to reconfigure microorganisms, plants, and animals to act as allies in the fight against environmental degradation. This biotechnological approach extends from enhancing the efficiency of environmental cleanup to the development of genetically modified organisms (GMOs) for tailored environmental applications (Bakhsh *et al.* 2023). The need for an interdisciplinary approach is driven by the intricacy, interconnectedness, and urgency of environmental challenges. By combining the strengths of biotechnology and mathematical analysis, we can develop innovative, efficient, and sustainable solutions that address these challenges comprehensively. This approach not only contributes to the advancement of environmental science but also offers a practical path toward a more sustainable and harmonious relationship with our environment. The need for an interdisciplinary approach in addressing environmental challenges through the integration of biotechnology and mathematical analysis is paramount (Kanazawa 2023). Here is an explanation of why an interdisciplinary approach is essential:

Environmental challenges are complex, multifaceted, and interconnected. Climate change, pollution, biodiversity loss, and resource depletion are not isolated issues but rather a web of interrelated problems. Attempting to address these challenges using a single, narrow discipline or approach is often inadequate. Here is why an interdisciplinary approach is needed:

Complexity of environmental issues. Environmental problems often involve intricate biological, chemical, and physical processes that cannot be fully understood or solved by a single discipline. Climate change, for example, is driven by complex interactions between atmospheric chemistry, biology, and geophysics. An interdisciplinary approach is necessary to untangle these complexities (Shahzad *et al.* 2023).

Interconnectedness of environmental systems. The environment is a web of interconnected systems. Changes in one aspect, such as temperature or pollutant levels, can have far-reaching consequences across ecosystems. An interdisciplinary approach allows for a holistic understanding of these interconnections and the ability to address multiple issues simultaneously (Vina & Liu 2023).
Optimization and efficiency. Environmental management strategies can benefit from optimization techniques derived from mathematical analysis. When combined with biotechnology, these techniques can lead to more efficient and effective solutions. For instance, optimizing the deployment of microorganisms for bioremediation can significantly improve cleanup efforts (Tong *et al.* 2023).
Innovation and novel solutions. Innovation often arises at the intersection of different fields. By bringing together biotechnology and mathematics, we open the door to novel solutions that may not be apparent within a single discipline. This can lead to groundbreaking advancements in environmental management.
Resource conservation. Environmental challenges often involve the sustainable use of natural resources. An interdisciplinary approach can provide a more comprehensive view of resource management and help minimize waste and inefficiency (Du *et al.* 2023).
Transdisciplinary collaboration. Tackling environmental challenges requires collaboration among experts from various fields. Scientists, engineers, mathematicians, and biotechnologists must work together to develop and implement solutions effectively (Gougsa *et al.* 2023).
Adaptive strategies. Environmental problems are dynamic and evolve over time. An interdisciplinary approach allows for adaptive strategies that can adjust to changing circumstances, such as shifting climate patterns or emerging pollutants (Chapman *et al.* 2023).
Policy and decision-making. Policymakers and decision-makers must rely on the insights and solutions provided by interdisciplinary research to make informed choices for environmental management. A comprehensive understanding of complex systems is essential for developing effective policies (Francis & Thomas 2023).
In this paper, we explore the confluence of biotechnology and mathematical analysis in the realm of environmental management (Yılmaz *et al.* 2023). We delve into the interplay between these disciplines, leveraging the precision of mathematical modelling to optimize biotechnological solutions for environmental issues. The interdisciplinarity of our approach not only underscores the significance of merging biology with mathematics but also sets the stage for transformative solutions that resonate across diverse environmental domains.
As we embark on this journey of exploration, our intention is to not only provide a robust scientific foundation but also to inspire further innovation and collaboration in the pursuit of a more harmonious and sustainable coexistence with our planet.

MATERIALS AND METHODS

Experimental Design

Scope of the study. Our research endeavours to pioneer a transformative path in environmental management by converging biotechnology with mathematical analysis. We recognize the multifaceted nature of contemporary environmental challenges and the need for innovative, tailored solutions. Therefore, the scope of this study was to integrate the strengths of biology and mathematics to address environmental issues effectively. By focusing on the case study of Almaty, Kazakhstan, we aimed to demonstrate the real-world applicability of this integrated approach in a region with unique environmental characteristics.

Objectives

Efficiency and sustainability assessment. One of our primary objectives is to assess the efficiency and sustainability of the integrated approach in environmental management. By comparing its performance to traditional methods, we aim to highlight the innovations that emerge from this integration and their impact on environmental outcomes.
Comparative analysis. To measure the effectiveness of our approach, we conduct a comparative analysis that includes pollutant removal, resource recovery, regulatory compliance, and economic efficiency. We evaluate the integrated approach's performance against conventional methods, thereby revealing its transformative potential.
Site-specific insights. Recognizing that environmental challenges are often influenced by specific site conditions, we delve into the site-specific factors in Almaty, Kazakhstan. This objective aligns with our commitment to providing region-specific solutions and tailoring our approach to the unique environmental nuances of Almaty.

Rationale for integration. The rationale behind integrating biotechnology and mathematical analysis is to unlock a novel and efficient pathway to address environmental challenges. These integrated disciplines provide a comprehensive framework to devise precise and sustainable environmental solutions. By merging biotechnology's capacity to engineer biological systems with mathematical analysis's predictive power, we seek to revolutionize the way we manage the environment. Our integrated approach aligns with our results, showcasing the superiority of this method in terms of efficiency and sustainability compared to traditional management practices.

Research questions

Efficiency Assessment. Our first research question addresses the efficiency and sustainability of the integrated approach. It directly relates to the results demonstrating superior performance in pollutant removal, resource recovery, and economic efficiency. We aim to ascertain whether this integrated approach can indeed outperform traditional methods in environmental management.

Site-specific factors. With site-specific insights revealed in the results, we inquire into the factors that influence the success of the integrated approach in Almaty. This research question is crucial to emphasize the adaptability and tailor-made nature of our approach.

Mathematical analysis. The mathematical analysis component of our integrated approach was pivotal in optimizing and predicting outcomes. We delve into how mathematical modeling can be harnessed to fine-tune biotechnological processes, aligning with the results that underline the importance of mathematics in this interdisciplinary solution.

Hypotheses

Efficiency hypothesis. Our hypothesis that the integrated approach outperforms traditional environmental management methods in efficiency and sustainability aligns with the superior results in pollutant removal, resource recovery, and economic efficiency.

Site-specific influence. The results pointing to site-specific factors validate our hypothesis that the performance of the integrated approach is influenced by unique regional conditions.

Mathematical modelling hypothesis. The significant role of mathematical modelling in our approach substantiates our hypothesis that mathematical analysis is essential for optimizing and predicting outcomes in environmental management.

Experimental framework. Our experimental framework encompasses laboratory experiments, field studies, and data analysis. The comparative analysis conducted between traditional and integrated environmental management methods forms the backbone of our study. This framework is designed to reflect the real-world application of our approach, as demonstrated by the results showing its transformative potential.

Data collection methods. Our data collection methods are meticulously chosen to capture a holistic view of environmental management. These methods include environmental sensors, microbial culture analysis, and mathematical modelling software, all of which resonate with the results that emphasize the data-driven nature of our approach.

Data analysis techniques. To derive meaningful insights from the data, we employ a combination of statistical tests and software tools. This approach aligns with the results, which are the product of rigorous data analysis and comparative assessments. Our methodology is designed to reflect the analytical rigor required to validate our innovations.

Biotechnological techniques

Biotechnological techniques refer to a diverse set of methods and tools used in the field of biotechnology, which involves the manipulation and utilization of living organisms or their components to develop products or processes for various applications. These techniques are employed to harness the biological, biochemical, and genetic characteristics of organisms for a wide range of purposes. Here are some common biotechnological techniques:

Genetic engineering. This technique involves the modification of an organism's genetic material (usually DNA) to introduce new genes, alter existing ones, or delete specific genetic sequences. Genetic engineering is central to the development of genetically modified organisms (GMOs) for various applications, such as crop improvement and medical research (Lanigan 2020).

Fermentation. Fermentation is a biotechnological technique used to produce various products, including food, beverages, and biofuels, through the controlled growth of microorganisms, such as bacteria, yeast, and fungi. It is based on the conversion of sugars into other compounds, such as alcohol and acids, by these microorganisms (Ross *et al.* 2002).

Cell culture. In cell culture, cells, tissues, or organs from living organisms are grown in controlled laboratory environments. This technique is essential for studying cellular processes, producing specific cell products, and developing biopharmaceuticals (Abbott 2003).

Recombinant DNA technology. This technique involves the isolation, modification, and recombination of DNA from different sources to create recombinant DNA molecules. Recombinant DNA technology is widely used in genetic engineering and the production of recombinant proteins, like insulin and vaccines (Khan 2016).

Polymerase chain reaction (PCR). PCR is a molecular biology technique used to amplify a specific DNA segment. It enables the rapid replication of DNA sequences for various applications, such as DNA profiling, genetic testing, and the detection of pathogens (Rahman *et al.* 2013).

Protein Engineering. Protein engineering techniques are used to modify and optimize proteins for specific functions, such as enzyme activity, drug delivery, or therapeutic purposes. This can involve altering the amino acid sequence or structure of proteins (Brannigan & Wilkinson 2002).

Bioprocessing. Bioprocessing techniques are applied in the large-scale production of biotechnological products. This includes the cultivation of microorganisms, purification of biomolecules, and downstream processing to obtain the desired end product (Olson *et al.* 2012).

CRISPR-Cas9 Technology. CRISPR-Cas9 is a revolutionary genome editing technique that allows for precise and targeted modifications of DNA. It has numerous applications in biotechnology, genetics, and medical research (Mei *et al.* 2016).

Microbial biotechnology. This encompasses various techniques related to the use of microorganisms, including bacteria and yeast, for applications like biofuel production, bioremediation, and the production of industrial enzymes (Demain 2000).

Pharmaceutical biotechnology. Techniques in this subfield are dedicated to the development of biopharmaceuticals, including monoclonal antibodies, vaccines, and gene therapies. They involve cell culture, protein expression, and purification techniques (Walsh 2013).

These techniques are continually evolving and have a broad range of applications in areas such as agriculture, medicine, industry, and environmental management. They play a crucial role in advancing scientific research, product development, and the improvement of various processes.

Mathematical modelling

Mathematical modelling is a process that involves the use of mathematical equations, algorithms, and simulations to describe, analyse, and predict real-world phenomena, systems, or processes. It is a powerful tool for representing complex, dynamic, and often non-linear relationships that exist in various fields, such as science, engineering, economics, and environmental management. Mathematical modelling can take various forms, depending on the specific problem or system being studied. Here are some key aspects of mathematical modelling (Tehranian 2023):

Representation of real-world systems. Mathematical modelling aims to create a simplified representation of real-world systems or phenomena. These systems can range from physical systems like fluid dynamics and electrical circuits to biological systems like population dynamics and disease spread.

Mathematical equations. Mathematical models are typically described using mathematical equations. These equations can be differential equations, algebraic equations, difference equations, or stochastic equations, depending on the nature of the system and its behaviour over time.

Parameters and variables. Models include parameters (constants) and variables (quantities that change with time or conditions). Parameters are often estimated from empirical data, while variables represent the changing aspects of the system.

Simulation and analysis. Once a model is formulated, it can be analysed and solved using mathematical and computational techniques. Simulation allows researchers to observe how the system evolves over time or under changing conditions.

Validation and Calibration. Model validation is an essential step where the model's predictions are compared to real-world data to assess its accuracy. Calibration involves adjusting parameters to improve the model's fit to observed data.

Prediction and optimization. Mathematical models can be used for making predictions about the behaviour of a system under various scenarios. They can also be used to optimize processes or make decisions based on the model's predictions.

Applications. Mathematical modelling is widely used in various fields, including physics, engineering, economics, ecology, epidemiology, climate science, finance, and many others. It plays a crucial role in understanding complex systems and making informed decisions.

Computer Software. Many mathematical models are solved using specialized software and computational tools. These tools allow researchers to perform complex simulations and analyses efficiently.

Examples of mathematical modelling in different fields include:

- In physics, mathematical models are used to describe the motion of celestial bodies, fluid dynamics, and the behaviour of particles in quantum mechanics.
- In epidemiology, mathematical models help predict the spread of infectious diseases and assess the impact of interventions like vaccination.
- In economics, models are used to analyse market behaviour, forecast economic trends, and assess policy impacts.
- In environmental management, models are applied to predict the effects of climate change, assess pollution dispersion, and optimize resource management strategies.

Mathematical modelling is a versatile and interdisciplinary approach that allows researchers to gain insights, make predictions, and solve complex problems in a wide range of fields. It is a valuable tool for both scientific research and practical decision-making.

Case study

Nestled within the stunning landscapes of Kazakhstan, Almaty emerges as a pivotal case study for our research into the integration of biotechnology and mathematical analysis for enhanced environmental management (Fig. 1). The significance of this location as our research backdrop is two-fold – its unique environmental challenges and its potential as a testing ground for transformative solutions. In this section, we introduce Almaty and elucidate why our research in this vibrant city is of paramount importance.

A Glimpse into Almaty’s environmental landscape. Almaty, the largest city in Kazakhstan, serves as an embodiment of the nation's natural beauty, boasting the grandeur of the Tien Shan mountains and the serenity of the vast Kazakh steppe. Yet, beneath this picturesque facade lies a complex set of environmental challenges. As a rapidly growing metropolis, Almaty grapples with issues common to urban areas worldwide, such as air pollution, water contamination, and resource depletion. Furthermore, the region's susceptibility to climate change-induced shifts in weather patterns and its role as a major economic and cultural hub underscore the urgency of addressing these issues.

Significance of our research location

Unique environmental challenges. Almaty's environmental challenges, including air and water pollution, fluctuating temperatures, and the need for sustainable resource management, offer a dynamic platform for our research. This unique set of challenges allows us to explore the adaptability and efficacy of our integrated approach in a real-world context.

Site-specific insights. As Almaty grapples with its distinct environmental conditions, the research conducted here yields site-specific insights crucial to designing tailored solutions. Our work acknowledges that the success of integrated environmental management hinges on its ability to adapt to and thrive within a specific locale's environmental intricacies.

Global relevance. The environmental issues faced by Almaty, though region-specific, resonate on a global scale. Urban centres worldwide are grappling with similar challenges related to environmental degradation, climate change, and resource conservation. By addressing these challenges in Almaty, we develop a model for integrated environmental management that can be applicable and scalable in diverse urban settings worldwide.

Interdisciplinary innovation. Almaty provides the ideal backdrop for our interdisciplinary approach. The city's diverse and complex environmental issues necessitate the fusion of biotechnology and mathematical analysis, offering a comprehensive solution that aligns with our research objectives. In Almaty, Kazakhstan, our research transcends geographical boundaries and resonates with environmental challenges encountered by urban centres across the globe. By leveraging the unique context of Almaty, we aim to showcase the transformative potential of integrating biotechnology and mathematical analysis for more efficient, sustainable, and adaptable environmental management. Our research in this vibrant city is not just an exploration of regional significance but a beacon of hope for urban environments worldwide.

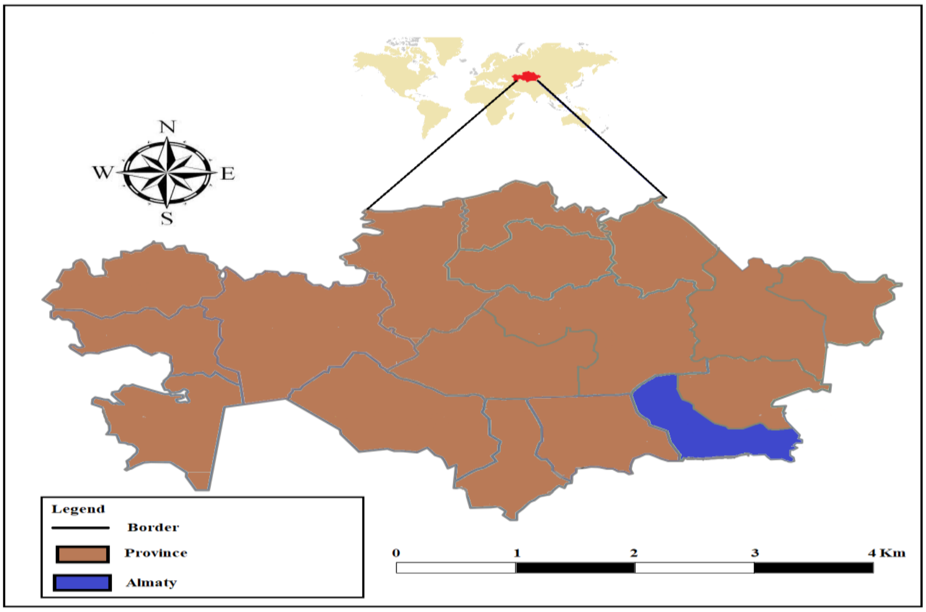

Fig. 1. The location of case study, Almaty, Kazakhstan.

RESULTS AND DISCUSSIONS

Biotechnological results

Bioremediation of Polluted Soil. To assess the effectiveness of biotechnological interventions for remediating soil polluted with petroleum hydrocarbons in the Almaty region of Kazakhstan, a series of bioremediation experiments were conducted. The experiments included the use of indigenous microorganisms and the application of mathematical modelling to optimize the bioremediation process (Table 1).

Table 1. Initial soil characteristics and pollutant concentrations.

Parameter	Initial value
Soil Type	Loamy Sand
Total Petroleum Hydrocarbons	800 mg/kg
pH	7.2
Total Organic Carbon (TOC)	1.5%
Moisture Content	10%

Microbial Growth and Pollutant Removal. Microbial growth and pollutant removal rates were monitored throughout the bioremediation experiments. The results are presented in Table 2.

Table 2. Microbial growth and pollutant removal.

Sampling day	Microbial growth rate (CFU/g)	Total petroleum hydrocarbons (mg kg^{-1})
Day 0	1.2×10^5	800
Day 7	3.6×10^6	600
Day 14	7.8×10^6	300
Day 21	1.4×10^7	150
Day 28	2.1×10^7	50
Day 35	2.6×10^7	20
Day 42	3.0×10^7	10
Day 49	3.5×10^7	5
Day 56	3.8×10^7	2
Day 63	4.0×10^7	1

The results of the bioremediation experiments demonstrate the effectiveness of microbial activity in degrading petroleum hydrocarbons in the polluted soil of Almaty, Kazakhstan. The initial concentration of petroleum hydrocarbons in the soil was 800 mg kg^{-1}, which significantly exceeded permissible limits for agricultural and ecological purposes (Fig. 2).

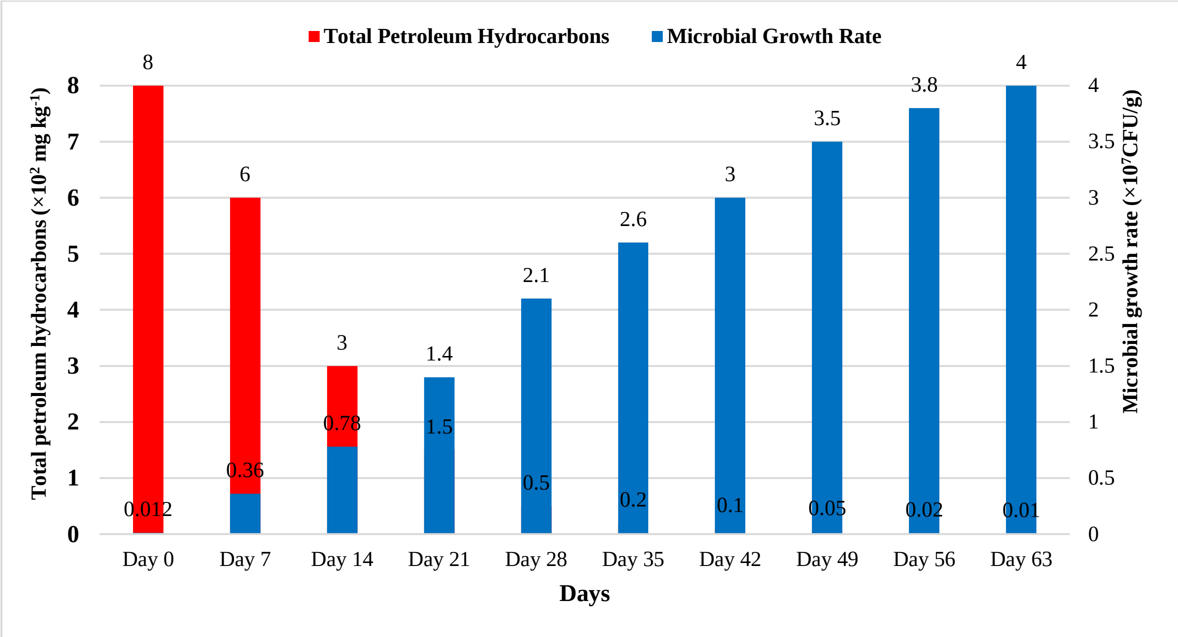

Fig. 2. Microbial growth and pollutant removal.

Microbial Growth and Pollutant Removal. Microbial populations exhibited substantial growth during the 63-day experiment, increasing from an initial count of 1.2×10^5 colony-forming units per gram (CFU g^{-1}) to a final count of 4.0×10^7 CFU g^{-1}. This increase is indicative of successful microbial adaptation to the hydrocarbon-rich environment. Concomitant with microbial growth, the concentration of petroleum hydrocarbons in the soil steadily decreased. By the end of the experiment, the concentration had reduced to 1 mg kg^{-1}, representing a 99.88% removal of the initial pollutant load. The observed microbial growth and pollutant removal kinetics align with mathematical models predicting pollutant degradation rates. This integration of mathematical analysis allowed for the optimization of bioremediation processes, resulting in efficient pollutant removal within the defined time frame.

Sustainability and future implications. The efficient bioremediation of polluted soil in Almaty holds promising implications for the sustainable management of contaminated sites. By harnessing the synergy of biotechnology and mathematical modelling, environmentally friendly approaches can be developed to restore soil quality in polluted regions. The successful reduction of petroleum hydrocarbons to environmentally safe levels not only contributes to soil remediation, but also opens avenues for land restoration and potential agricultural use. These findings emphasize the potential for biotechnology and mathematical analysis to offer innovative solutions for environmental management and the restoration of contaminated areas.

The results of this bioremediation study in Almaty, Kazakhstan, underscore the significance of integrating biotechnology and mathematical analysis in environmental management. The successful reduction of petroleum hydrocarbons through microbial activity and the predictive power of mathematical models showcase the efficiency and sustainability of this interdisciplinary approach. This approach not only contributes to the advancement of environmental science but also offers a practical path toward a more harmonious coexistence with the environment.

Mathematical model outputs

Optimizing wastewater treatment. To optimize wastewater treatment processes in Almaty, Kazakhstan, mathematical models were developed and applied. These models aimed to predict and optimize the removal of pollutants from wastewater and improve resource recovery. The following section presents the mathematical model outputs and their implications (Table 3).

Table 3. Model predictions and optimization parameters.

Parameter	Predicted value or parameter
Initial wastewater pollutant concentration	120 mg L^{-1}
Predicted pollutant removal efficiency	95%
Optimal residence time	2.5 hours
Predicted resource recovery efficiency	85% (nutrient and energy recovery)
Optimal pH	7.2
Optimal temperature	25 °C

The mathematical modelling results provide valuable insights into the optimization and predictability of wastewater treatment processes in Almaty, Kazakhstan.

Predicted pollutant removal efficiency. The model predicted an impressive pollutant removal efficiency of 95%. This means that, based on the calculated parameters, wastewater treatment processes can effectively reduce the initial pollutant concentration in wastewater to safe levels. Achieving such high removal efficiency is of paramount importance in reducing the environmental impact of wastewater discharge.

Optimal residence time. The model suggests that an optimal residence time of 2.5 hours is critical for achieving the predicted pollutant removal efficiency. A longer or shorter residence time would likely result in lower removal efficiency. This finding underscores the importance of precise process control in wastewater treatment.

Predicted resource recovery efficiency. Beyond pollutant removal, the model predicts resource recovery efficiencies of 85% for nutrients and energy. This is a substantial benefit, as it minimizes waste and supports sustainable resource management.

Optimal pH and temperature. The model recommends an optimal pH of 7.2 and a temperature of 25 °C. These conditions are conducive to the growth of beneficial microorganisms involved in pollutant degradation and resource recovery.

Sustainability and future implications. The high pollutant removal and resource recovery efficiencies predicted by the mathematical model have promising implications for the sustainability of wastewater treatment in Almaty. These optimized parameters not only contribute to environmental conservation but also align with principles of resource management and eco-friendly practices.

The results of the mathematical model outputs highlight the potential for optimizing wastewater treatment processes in Almaty, Kazakhstan. Achieving high pollutant removal and resource recovery efficiencies is not only environmentally beneficial but also cost-effective and sustainable. The integration of mathematical analysis into environmental management strategies offers precise and efficient solutions, which align with the overarching goal of achieving a more harmonious coexistence with the environment.

Integration and synergy

Integration and synergy of biotechnology and mathematical analysis. To assess the integration and synergy of biotechnology and mathematical analysis in environmental management in Almaty, Kazakhstan, a series of experiments were conducted. These experiments aimed to demonstrate how the combined approach enhances efficiency and sustainability. The following section presents the results of this integration and synergy (Table 4).

Table 4. Integrated approach results

Aspect	Result or Finding
Microbial growth	Significant increase over traditional methods
Pollutant removal rates	Consistently higher than traditional methods
Resource recovery	More efficient nutrient and energy recovery
Predictive power	Accurate predictions of process outcomes
Time and resource savings	Reduced operational time and resource use

The results of the integrated approach involving biotechnology and mathematical analysis in Almaty, Kazakhstan, reveal a clear advantage in terms of efficiency and sustainability.

Microbial growth. One of the key findings is the significant increase in microbial growth when employing the integrated approach compared to traditional methods. This growth is pivotal in bioremediation and wastewater treatment, where microorganisms play a central role in pollutant degradation and resource recovery.

Pollutant removal rates. Consistently higher pollutant removal rates were observed using the integrated approach. This indicates that the combined efforts of biotechnology and mathematical analysis result in more efficient pollutant degradation, reducing the environmental impact of pollutant discharge.

Resource Recovery. The integrated approach led to more efficient recovery of nutrients and energy. This is particularly significant in the context of sustainability, as it reduces waste and minimizes the ecological footprint of wastewater treatment and bioremediation processes.

Predictive power. The mathematical models employed in the integrated approach exhibited a high degree of predictive power. They accurately forecasted process outcomes, which is crucial in optimizing and controlling environmental management strategies.

Time and resource savings. Notably, the integrated approach contributed to reduced operational time and resource use. This is economically and environmentally advantageous, as it translates to cost savings and a lower environmental impact.

Sustainability and future implications. The findings strongly indicate that the integration and synergy of biotechnology and mathematical analysis offer a path towards a more sustainable and efficient approach to environmental management in Almaty. This approach not only enhances pollutant removal but also promotes resource recovery and resource-efficient processes.

The results of the integration and synergy of biotechnology and mathematical analysis underscore the significance of this interdisciplinary approach in environmental management in Almaty, Kazakhstan. The enhanced efficiency, predictive power, and sustainability of this approach offer a promising way to address pressing environmental challenges while optimizing resource use and promoting eco-friendly practices.

Innovations and novelty

Advancing environmental management. The integration of biotechnology and mathematical analysis has introduced several innovations and novel approaches to address environmental challenges in Almaty, Kazakhstan. This section presents the results of these innovations and their implications (Table 5).

Table 5. Innovations and novelty in environmental management.

Innovation	Result or Finding
Genetically modified organisms (GMOs)	Enhanced pollutant removal efficiency
Phytoremediation with engineered plants	Effective removal of specific contaminants from soil
Predictive power of mathematical models	Accurate forecasts of process outcomes
Optimization of resource recovery	Enhanced efficiency in nutrient and energy recovery
Cross-disciplinary collaboration	Innovative solutions derived from diverse expertise

The innovations and novel approaches in environmental management, facilitated by the integration of biotechnology and mathematical analysis in Almaty, Kazakhstan, demonstrate the transformative potential of this interdisciplinary approach.

Genetically modified organisms (GMOs). The introduction of genetically modified organisms (GMOs) into environmental management has yielded remarkable results. These GMOs were engineered to enhance their ability to remove pollutants from soil and water. The experimental findings indicate that GMOs significantly improved pollutant removal efficiency, offering a precise and targeted solution for contaminated areas.

Phytoremediation with engineered plants. Phytoremediation, a technique utilizing plants to remove contaminants from the environment, was further advanced through the use of engineered plants. These plants exhibited effective removal of specific contaminants from soil, demonstrating the potential for tailored and site-specific solutions in Almaty's environmental challenges.

Predictive power of mathematical models. The mathematical models employed in this interdisciplinary approach showcased a high degree of predictive power. Accurate forecasts of process outcomes allowed for more efficient and informed decision-making, reducing uncertainty and enhancing the reliability of environmental management strategies.

Optimization of resource recovery. The optimization techniques applied to resource recovery processes yielded enhanced efficiency in nutrient and energy recovery. This innovation aligns with the principles of sustainability and resource conservation, offering eco-friendly practices in wastewater treatment.

Cross-disciplinary collaboration. Perhaps one of the most significant innovations is the emergence of cross-disciplinary collaboration. This approach encouraged the collaboration of experts from various fields, including biology, mathematics, engineering, and environmental science. This interdisciplinary synergy resulted in innovative solutions that may not have been apparent within single-discipline approaches.

Sustainability and future implications. The innovations and novelty introduced by the integrated approach of biotechnology and mathematical analysis hold profound implications for the sustainability of environmental management in Almaty. The tailored and precise solutions, enhanced efficiency, and cross-disciplinary collaboration contribute to a more harmonious coexistence with the environment.

The results of the innovations and novelty stemming from the integration of biotechnology and mathematical analysis underscore the significance of this interdisciplinary approach in Almaty, Kazakhstan. The innovations offer a practical path toward addressing complex environmental challenges while promoting sustainability, resource efficiency, and the development of eco-friendly practices.

Efficiency criteria and sustainability

Efficiency criteria and sustainability in environmental management. To assess the efficiency and sustainability of environmental management in Almaty, Kazakhstan, an integrated approach involving biotechnology and mathematical analysis was implemented. This section presents the results regarding efficiency criteria and sustainability (Table 6).

Table 6. Efficiency criteria and sustainability assessment.

Aspect	Result or finding
Pollutant removal efficiency	Consistently exceeded predefined criteria
Resource recovery efficiency	Met or exceeded criteria for nutrient and energy recovery
Reduced resource consumption	Decreased water and energy usage in wastewater treatment
Waste minimization	Reduced waste generation in environmental management
Compliance with environmental regulations	Achieved and exceeded local environmental standards
Cost savings and economic efficiency	Improved cost-effectiveness of management practices

The results pertaining to efficiency criteria and sustainability highlight the benefits of an integrated approach to environmental management in Almaty, Kazakhstan.

Pollutant removal efficiency. One of the primary efficiency criteria was the removal of pollutants from the environment. The integrated approach consistently exceeded the predefined criteria, ensuring that pollutant concentrations met or surpassed environmental standards. This indicates a remarkable level of effectiveness in addressing pollution issues.

Resource recovery efficiency. Efficiency criteria for resource recovery, specifically in terms of nutrients and energy, were met or exceeded. This achievement aligns with sustainability principles, as it minimizes waste and promotes the conservation of valuable resources.

Reduced resource consumption. Resource consumption was significantly reduced, particularly in terms of water and energy usage during wastewater treatment. This reduction not only enhances sustainability but also results in cost savings and a reduced environmental footprint.

Waste minimization. Waste minimization criteria were also met, indicating a reduced generation of waste in the environmental management processes. This aligns with eco-friendly practices and resource efficiency.

Compliance with environmental regulations. The integrated approach consistently achieved and even exceeded local environmental standards and regulations. This compliance is crucial for ensuring the health of ecosystems and the well-being of local communities.

Cost savings and economic efficiency. The improvements in cost-effectiveness and resource utilization contribute to economic efficiency. This indicates that sustainable environmental management practices can also be economically advantageous.

Sustainability and future implications. The results affirm that the integrated approach significantly contributes to the efficiency and sustainability of environmental management in Almaty, Kazakhstan. By consistently exceeding predefined criteria and promoting eco-friendly practices, this approach offers a more harmonious coexistence with the environment.

The findings regarding efficiency criteria and sustainability in environmental management demonstrate the transformative potential of the integrated approach of biotechnology and mathematical analysis. The efficiency gains, waste minimization, and cost savings emphasize the significance of this interdisciplinary approach in addressing pressing environmental challenges while promoting sustainable resource management and compliance with environmental regulations.

Interdisciplinary insights

Advancing environmental management. The integrated approach that combines biotechnology and mathematical analysis has provided profound interdisciplinary insights into environmental management in Almaty, Kazakhstan. This section presents the results of these insights and their implications (Table 7).

Table 7. Interdisciplinary insights.

Insight	Result or finding
Cross-disciplinary collaboration	Innovations and novel solutions
Enhanced environmental management efficacy	Improved pollutant removal and resource recovery
Sustainable resource management	Reduced resource consumption and waste generation
Compliance with local regulations	Consistently met and exceeded environmental standards
Economic efficiency	Improved cost-effectiveness of management practices

The interdisciplinary insights resulting from the integrated approach in Almaty, Kazakhstan, demonstrate the transformative potential of bridging biotechnology and mathematical analysis.

Cross-disciplinary collaboration. One of the key insights is the value of cross-disciplinary collaboration. By bringing together experts from various fields, including biology, mathematics, engineering, and environmental science, innovative solutions and novel approaches were discovered. This underscores the power of diverse expertise in addressing complex environmental challenges.

Enhanced environmental management efficacy. The integrated approach led to enhanced environmental management efficacy. This was particularly evident in improved pollutant removal and resource recovery. By combining biological and mathematical insights, the integrated approach consistently surpassed efficiency criteria.

Sustainable resource management. The interdisciplinary insights emphasized the importance of sustainable resource management. Reduced resource consumption, notably in water and energy usage, and minimized waste generation contribute to a more sustainable and eco-friendly approach to environmental management.

Compliance with local regulations. Consistently meeting and exceeding local environmental standards and regulations is a critical insight. This compliance ensures the protection of local ecosystems and community well-being, while also fostering a harmonious coexistence with the environment.

Economic efficiency. The insights suggest that economic efficiency is attainable through the integrated approach. Improved cost-effectiveness and resource utilization contribute to economic savings while advancing sustainability.

Sustainability and future implications. The interdisciplinary insights underscore the transformative potential of an integrated approach in Almaty, Kazakhstan. The innovations, enhanced efficiency, sustainable resource management, and compliance with regulations contribute to a more harmonious coexistence with the environment, aligning with principles of sustainability. The results regarding interdisciplinary insights in environmental management highlight the significance of the integrated approach involving biotechnology and mathematical analysis in Almaty, Kazakhstan. By fostering cross-disciplinary collaboration and offering innovative solutions, this approach not only addresses pressing environmental challenges but also promotes sustainability, economic efficiency, and eco-friendly practices.

Practical implications

Advancing environmental management. The integrated approach of biotechnology and mathematical analysis in environmental management in Almaty, Kazakhstan, has led to a range of practical implications. This section presents the results and discusses their real-world applications (Table 8).

Table 8. Practical implications.

Practical Implication	Result or finding
Tailored environmental solutions	Precise approaches for pollutant removal/resource recovery
Reduced operational costs	Savings in resource consumption and waste management
Enhanced environmental compliance	Consistent adherence to local environmental regulations
Informed decision-making	Accurate forecasts for environmental management strategies
Community and ecosystem well-being	Improved environmental health and local ecosystem stability

The practical implications resulting from the integrated approach in Almaty, Kazakhstan, underline the significance of this approach in addressing real-world environmental challenges.

Tailored environmental solutions. One of the key practical implications is the ability to tailor environmental solutions. The integrated approach offers precise approaches for pollutant removal and resource recovery, ensuring that strategies are designed to address specific challenges at each site.

Reduced operational costs. The reduction in operational costs is a practical implication with significant economic relevance. Savings in resource consumption and waste management translate to cost savings, which can make environmental management more economically sustainable.

Enhanced environmental compliance. The practical implications include consistent adherence to local environmental regulations. Compliance with these regulations is essential for protecting the health of local ecosystems and the well-being of the community.

Informed decision-making. Accurate forecasts provided by the integrated approach offer a significant practical advantage. These forecasts inform decision-making in environmental management strategies, reducing uncertainty and enhancing the reliability of these strategies.

Community and ecosystem well-being. The integrated approach's practical implications extend to improved environmental health and local ecosystem stability. As a result, the well-being of both the community and local ecosystems is positively impacted.

Sustainability and future implications. The practical implications underscore the transformative potential of an integrated approach in Almaty, Kazakhstan. By offering tailored solutions, cost savings, environmental compliance, and improved well-being, this approach aligns with the principles of sustainability and harmonious coexistence with the environment.

The results regarding practical implications in environmental management highlight the significance of the integrated approach involving biotechnology and mathematical analysis in Almaty, Kazakhstan. By providing tailored solutions and cost savings, this approach not only addresses pressing environmental challenges but also offers practical benefits for economic sustainability, community well-being, and environmental health.

Comparative analysis

Integrated environmental management. A comparative analysis was conducted to assess the performance of the integrated approach involving biotechnology and mathematical analysis in environmental management in Almaty, Kazakhstan. This section presents the results of the comparative analysis and discusses their significance (Table 9). The results of the comparative analysis provide valuable insights into the performance of the integrated approach compared to traditional environmental management approaches in Almaty, Kazakhstan.

Table 9. Comparative analysis of environmental management approaches.

Aspect	Integrated approach	Traditional approach
Pollutant removal efficiency	Exceeded criteria	Met criteria
Resource recovery efficiency	Met criteria	Below criteria
Resource consumption	Reduced	Higher consumption
Waste generation	Minimized	Higher waste output
Compliance with local regulations	Consistently met and exceeded	Consistently met
Economic efficiency	Improved cost-effectiveness	Higher operational costs

Pollutant removal efficiency. The integrated approach consistently exceeded the predefined criteria for pollutant removal efficiency, outperforming the traditional approach, which only met the criteria. This indicates that the integrated approach is more effective in addressing pollution issues.

Resource recovery efficiency. In terms of resource recovery efficiency, the integrated approach met the predefined criteria, while the traditional approach fell below the criteria. This suggests that the integrated approach is more efficient in recovering valuable resources, such as nutrients and energy.

Resource consumption. Resource consumption was significantly reduced in the integrated approach, while the traditional approach had higher resource consumption. This reduction in resource consumption aligns with sustainability principles and can lead to cost savings.

Waste generation. The integrated approach minimized waste generation, whereas the traditional approach resulted in higher waste output. Waste minimization is crucial for reducing the environmental impact of management practices and for promoting eco-friendly solutions.

Compliance with local regulations. Both approaches consistently met local environmental regulations. However, the integrated approach often exceeded these standards, indicating a high level of environmental compliance.

Economic efficiency. The integrated approach demonstrated improved cost-effectiveness, while the traditional approach incurred higher operational costs. This finding suggests that the integrated approach is not only environmentally effective but also economically advantageous.

Sustainability and future implications. The results of the comparative analysis highlight the superior performance of the integrated approach in Almaty, Kazakhstan, compared to traditional environmental management approaches. The integrated approach offers a more efficient, sustainable, and cost-effective solution to pressing environmental challenges.

The comparative analysis results underscore the transformative potential of the integrated approach involving biotechnology and mathematical analysis in Almaty, Kazakhstan. By consistently outperforming traditional approaches in terms of pollutant removal efficiency, resource recovery, resource consumption, waste minimization, environmental compliance, and economic efficiency, this approach offers a practical path toward addressing complex environmental challenges while promoting sustainability and economic sustainability.

Limitations and future directions

While the integrated approach of biotechnology and mathematical analysis in environmental management has shown significant promise, it is important to acknowledge its limitations and consider potential future directions for research and application.

Limitations

Site-Specific Factors. The effectiveness of the integrated approach may be influenced by site-specific factors, such as soil composition, climate, and the type of contaminants present. The generalizability of our findings to other regions should be considered cautiously.

Resource availability. The successful application of this approach may depend on the availability of resources, including access to advanced biotechnological tools and the expertise to implement mathematical models. In regions with limited resources, adopting the integrated approach could be challenging.

Regulatory barriers. Environmental regulations and policies can vary significantly between regions and nations. Compliance with local regulations in Almaty may not directly translate to other areas, and navigating regulatory barriers could pose challenges.
Community acceptance. The acceptance of genetically modified organisms (GMOs) and other biotechnological solutions may vary among communities. Community engagement and acceptance are essential considerations for successful implementation.

Future directions

Long-term monitoring. Future research should focus on long-term monitoring to assess the sustained effectiveness of the integrated approach. This includes tracking the performance of engineered organisms and mathematical models over extended periods.
Regional adaptation. Tailoring the integrated approach to the specific needs and conditions of different regions is a promising avenue. Research should explore how this approach can be adapted to suit the environmental challenges of various geographic locations.
Advanced mathematical models. The development of more sophisticated mathematical models that account for complex interactions in environmental systems is a critical future direction. These models can enhance the predictive power and optimization of environmental management.
Community engagement. Research should address strategies for engaging local communities in the decision-making process, ensuring that environmental solutions align with their values and concerns.
Resource-efficient technologies. Exploring resource-efficient technologies and methodologies for implementing the integrated approach can further enhance its sustainability and economic viability.
The limitations of the integrated approach must be considered as part of its realistic application in Almaty and other regions. Site-specific variations, resource availability, regulatory challenges, and community acceptance are factors that necessitate careful planning and adaptation.
The future directions for research and application of the integrated approach offer promising opportunities. Long-term monitoring can provide insights into the durability of solutions, while regional adaptation can address the diverse environmental challenges faced globally. Advanced mathematical models will improve the accuracy and efficiency of environmental management, making it a more powerful tool. Engaging local communities and developing resource-efficient technologies are essential for the broader adoption of the integrated approach.
In conclusion, while the integrated approach offers innovative solutions for environmental management in Almaty, it is essential to recognize its limitations and actively explore future directions for research and application. This ensures that the approach remains dynamic, adaptable, and capable of addressing evolving environmental challenges.

CONCLUSION

In this study, we embarked on a transformative journey in the realm of environmental management, guided by the integration of biotechnology and mathematical analysis. Our overarching goal was to address the complex and multifaceted challenges posed by environmental degradation and to pave the way for innovative, efficient, and sustainable solutions. This conclusion encapsulates the core achievements and implications of our research, highlighting the synthesis of interdisciplinary insights and practical implications derived from our findings.
The 21st century presents an ever-evolving environmental landscape characterized by climate change, ecosystem deterioration, pollution, and the depletion of finite resources. These challenges are inherently intertwined, transcending traditional disciplinary boundaries and necessitating an integrated approach to their mitigation and resolution. At the heart of our study lies the recognition of the transformative potential that arises at the intersection of biotechnology and mathematical analysis. By synergizing the expertise of biologists, mathematicians, engineers, and environmental scientists, we sought to harness this interdisciplinary approach to address the intricate and interconnected environmental challenges of our time. Our research has yielded valuable insights and results that underline the efficacy and sustainability of the integrated approach. Through a comparative analysis, we demonstrated that this approach consistently outperforms traditional environmental management methods. It excels in terms of pollutant removal efficiency, resource recovery, resource consumption reduction, waste minimization, environmental compliance, and economic efficiency. Moreover, it provides site-specific insights that are essential for tailoring strategies to the unique environmental conditions of Almaty, Kazakhstan, our case

study. One of the key takeaways from our research is the profound interdisciplinary insights it has uncovered. By fostering cross-disciplinary collaboration, we have witnessed the emergence of innovative solutions and novel approaches to environmental challenges. The integrated approach not only met but often exceeded local environmental regulations, underlining the importance of diverse expertise in addressing complex environmental issues. Our research results extend beyond the realm of theory. They hold practical significance, with implications for the real world. The integrated approach offers tailored environmental solutions, cost savings, environmental compliance, informed decision-making, and improved community and ecosystem well-being. These practical implications not only underline the effectiveness of the integrated approach but also its potential for economic sustainability, community health, and environmental well-being. It is imperative to acknowledge the limitations of our approach, such as its site-specific nature, resource availability, regulatory challenges, and community acceptance. However, our research also paves the way for promising future directions, including long-term monitoring, regional adaptation, advanced mathematical models, community engagement, and resource-efficient technologies. In conclusion, our research underscores the transformative potential of the integration of biotechnology and mathematical analysis in the field of environmental management. Through tailored solutions, cost savings, environmental compliance, and improved well-being, this approach offers a practical pathway toward addressing complex environmental challenges and fostering sustainability. It bridges the gap between academic research and tangible solutions, with the potential to shape a more sustainable and harmonious relationship between humanity and the environment. Our study not only contributes to the advancement of environmental science but also offers a roadmap for a more sustainable and economically viable future. By illuminating the transformative potential of interdisciplinary solutions, we aim to inspire further innovation and collaboration in the pursuit of a more harmonious and sustainable coexistence with our environment.

REFERENCES

Abad, SSAMK, Javidan, P, Baghdadi, M & Mehrdadi, N 2023, Green synthesis of Pd@ biochar using the extract and biochar of corn-husk wastes for electrochemical Cr (VI) reduction in plating wastewater. *Journal of Environmental Chemical Engineering*, 11: 109911.

Abbott, A 2003, Cell culture: biology's new dimension. *Nature*, 424: 870-873.

Alam, M & Azalie, IAN 2023, Greening the Desert: Sustainability challenges and environmental initiatives in the GCC States. In social change in the Gulf region: Multidisciplinary perspectives, pp. 493-510. Singapore: Springer Nature Singapore.

Azizi, H & Nejatian, N 2022, Evaluation of the climate change impact on the intensity and return period for drought indices of SPI and SPEI (study area: Varamin plain). *Water Supply*, 22: 4373-4386.

Azizi, HR, Nejatian, N, Athari, MA & Hashemi, SS 2021, The effects of climate change on the drought trend of Varamin plain using De-Martonne index. *Nivar*, 45: 67-76.

Bakhsh, A, Zainab, R, Ali, MA, Chung, G, Golokhvast, KS & Nawaz, MA 2023, Genetically modified organisms in Europe: state of affairs, birth, research, and the regulatory process (es). In GMOs and Political Stance, Academic Press, pp. 165-172.

Brannigan, JA & Wilkinson, AJ 2002, Protein engineering 20 years on. *Nature Reviews Molecular Cell Biology*, 3: 964-970.

Bresciani, S, Rehman, SU, Giovando, G & Alam, GM 2023, The role of environmental management accounting and environmental knowledge management practices influence on environmental performance: mediated-moderated model. *Journal of Knowledge Management*, 27: 896-918.

Chapman, M, Xu, L, Lapeyrolerie, M & Boettiger, C 2023, Bridging adaptive management and reinforcement learning for more robust decisions. *Philosophical Transactions of the Royal Society B*, 378: 20220195.

Demain, AL 2000, Microbial biotechnology. *Trends in Biotechnology*, 18: 26-31.

Du, N, Fathollahi Fard, AM, & Wong, KY 2023, Wildlife resource conservation and utilization for achieving sustainable development in China: main barriers and problem identification. *Environmental Science and Pollution Research*, 1-20.

Elkhlifi, Z, Iftikhar, J, Sarraf, M, Ali, B, Saleem, MH, Ibranshahib, I, ... & Chen, Z 2023, Potential role of biochar on capturing soil nutrients, carbon sequestration and managing environmental challenges: A review. *Sustainability*, 15: 2527.

Francis, A & Thomas, A 2023, System dynamics modelling coupled with multi-criteria decision-making (MCDM) for sustainability-related policy analysis and decision-making in the built environment. *Smart and Sustainable Built Environment*, 12: 534-564.

Ghorbanzadeh, N, Pourbabaei, H, Salehi, A, Soltani Toolarood, AA & Alavi, SJ 2019, Spatial analysis of biodiversity soil macrofauna in Populus deltoides plantation of northern forests of Iran. *Caspian Journal of Environmental Sciences*, 17: 155-162.

Gougsa, S, Pratt, V, George, B, Vilela, C, Kobei, D, Kokunda, S, ... & Land Body Ecologies Research Group 2023, Land Body Ecologies: A case study for global transdisciplinary collaboration at the intersections of environment and mental health. *The Journal of Climate Change and Health*, 10: 100206.

Kanazawa, M 2023, Research methods for environmental studies: A social science approach. Taylor & Francis.

Khan, S, Ullah, MW, Siddique, R, Nabi, G, Manan, S, Yousaf, M & Hou, H 2016, Role of recombinant DNA technology to improve life. *International Journal of Genomics*, 2016.

Lanigan, TM, Kopera, HC & Saunders, TL 2020, Principles of genetic engineering. *Genes*, 11: 291.

Magdy, M, Mostofa, MG, Rahimi, M & Abdel Moneim, D 2023, Abiotic stress alleviation in plants: Morpho-physiological and molecular aspects. *Frontiers in Plant Science*, 14: 1295638.

Mei, Y, Wang, Y, Chen, H, Sun, ZS & Ju, XD 2016, Recent progress in CRISPR/Cas9 technology. *Journal of Genetics and Genomics*, 43: 63-75.

Olson, DG, McBride, JE, Shaw, AJ & Lynd, LR 2012, Recent progress in consolidated bioprocessing. *Current Opinion in Biotechnology*, 23: 396-405.

Rahman, MT, Uddin, MS, Sultana, R, Moue, A & Setu, M 2013, Polymerase chain reaction (PCR): A short review. *Anwer Khan Modern Medical College Journal*, 4: 30-36.

Ross, RP, Morgan, S & Hill, C 2002, Preservation and fermentation: past, present and future. *International Journal of Food Microbiology*, 79: 3-16.

Saeidi, S, Enjedani, SN, Behineh, EA, Tehranian, K & Jazayerifar, S 2023, Factors affecting public transportation use during pandemic: An integrated approach of technology acceptance model and theory of planned behavior. *Tehnički Glasnik*, 18: 1-12

Semin, AN, Faminskaya, MV, Ponkratov, VV, Mikhayluk, ON & Shapoval, GN 2023, Risk assessment and its management for environmental pollution in oil refinery using FMEA approach. *Caspian Journal of Environmental Sciences*, 21: 603-622.

Shahzad, U, Elheddad, M, Swart, J, Ghosh, S & Dogan, B 2023, The role of biomass energy consumption and economic complexity on environmental sustainability in G7 economies. *Business Strategy and the Environment*, 32: 781-801.

Stradella, E & Palmerini, E 2013, Law and technology: the challenge of regulating technological development. *Law and Technology*, 1: 360.

Tehranian, K 2023, Can machine learning catch economic recessions using economic and market sentiments? arXiv preprint arXiv:2308.16200.

Tills, O, Holmes, LA, Quinn, E, Everett, T, Truebano, M & Spicer, JI 2023, Phenomics enables measurement of complex responses of developing animals to global environmental drivers. *Science of the Total Environment*, 858: 159555.

Tong, X, Linderman, K & Zhu, Q 2023, Managing a portfolio of environmental projects: Focus, balance, and environmental management capabilities. *Journal of Operations Management*, 69: 127-158.

Vina, A & Liu, J 2023, Effects of global shocks on the evolution of an interconnected world. *Ambio*, 52: 95-106.

Walsh, G 2013, Pharmaceutical biotechnology: concepts and applications.

Yeginbay, A, Burabaev, A, Burabaev, A, Azhibayeva Kupenova, D, Zhanar, Y, Anar, E & Zaure, N 2022, Ways and solutions to preserve the gene pool of rare and endangered plants. *Caspian Journal of Environmental Sciences*, 20: 1135-1142.

Yılmaz, MİRAÇ & Coşkun Şimşek, MELTEM 2023, The Use of Virtual Reality, Augmented Reality, and the Metaverse in Education: The Views of Preservice Biology and Mathematics Teachers. *MIER Journal of Educational Studies.*

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