SCIENCE, SUSTAINABILITY, AND TECHNOLOGY:

Contemporary Research and Applications

The Selected Chapters

WAH ACADEMIA PUBLISHING

Science, Sustainability, and Technology:
Contemporary Research and Applications
The Selected Chapters

Science, Sustainability, and Technology:
Contemporary Research and Applications

Wah Academia Publishing

Editors

Zeliha Selamoglu
Department of Medical Biology, Medicine Faculty, Nigde Omer Halisdemir University, Nigde, Türkiye

Department of Biology, Faculty of Sciences, Khoja Akhmet Yassawi International Kazakh-Turkish University, Turkestan, Kazakhstan

Dilara Sunakbaeva
Department of Ecology and Chemistry, Faculty of Natural Sciences, Khoja Akhmet Yassawi International Kazakh-Turkish University, Turkestan, Kazakhstan

ISBN 978-627-7901-15-8

© The Editor(s) (if applicable) and The Author(s) 2026. This book is an open access publication.

Open Access This book is licensed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.
The images or other third-party material in this book are included in the book's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the book's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This *WAP* imprint is published by the registered company Wah Academia (SMC-PVT) Ltd: Wah Cantt, Pakistan. (2026)

If disposing of this product, please recycle the paper.

To our families, friends, and loved ones.

Preface

Science, sustainability, and technology stand at the heart of contemporary efforts to understand and respond to the complex challenges of the modern world. Rapid industrial growth, environmental degradation, public health concerns, and the accelerated integration of digital technologies have reshaped how knowledge is produced and applied. This volume brings together scholarly contributions that reflect these evolving realities, highlighting how scientific inquiry and technological innovation can be directed toward sustainable and socially responsible outcomes.

The chapters collected in this book represent diverse yet interconnected fields, including environmental and plant sciences, public and environmental health, and the transformative role of modern technologies in education and medical training. While each chapter addresses a distinct research problem, all are united by a shared commitment to evidence-based analysis and practical application. Together, they demonstrate how interdisciplinary research can generate solutions that are both innovative and grounded in real-world needs.

Sustainability is treated in this volume not as an abstract ideal, but as an actionable framework guiding scientific and technological progress. From nature-based approaches to environmental remediation to the responsible use of artificial intelligence in education and healthcare, the contributions emphasize resilience, adaptability, and long-term impact. The studies presented here illustrate how thoughtful integration of science and technology can enhance environmental protection, improve human well-being, and strengthen institutional capacity.

This book is intended for researchers, educators, policymakers, and practitioners who seek a deeper understanding of contemporary scientific applications within a sustainability-oriented perspective. By fostering dialogue across disciplines, this volume aims to encourage critical reflection, inspire future research, and support informed decision-making. It is our hope that the insights offered here will contribute meaningfully to ongoing efforts to shape a more sustainable, innovative, and equitable future.

Turkestan, Kazakhstan
2026

Zeliha Selamoglu
Dilara Sunakbaeva

Acknowledgments: The editors would like to express their sincere gratitude to all the authors whose scholarly contributions form the foundation of this volume. Their dedication to rigorous research, intellectual curiosity, and commitment to advancing knowledge across diverse disciplines have made this book possible. Each chapter reflects careful inquiry and thoughtful engagement with contemporary scientific, technological, and sustainability-related challenges.

We are also thankful to the reviewers and academic colleagues who provided valuable feedback and constructive suggestions during the development of this book. Their insights helped strengthen the quality, clarity, and coherence of the chapters, ensuring that the volume meets high academic and ethical standards. The collaborative spirit of peer review remains essential to the advancement of credible and impactful scholarship.

Our appreciation extends to the editorial and production team whose professionalism and attention to detail guided this work from manuscript to publication. Their patience, technical expertise, and consistent support were instrumental in coordinating contributions, maintaining academic integrity, and ensuring a smooth publication process.

Competing Interests: The authors have no conflicts of interest to declare that are relevant to the content of this book.

About This Book

This open-access peer-reviewed book, ***Science, Sustainability, and Technology: Contemporary Research and Applications*** brings together a collection of scholarly chapters that examine how scientific knowledge and technological innovation are being applied to address pressing environmental, health, and educational challenges. The book adopts an interdisciplinary perspective, recognizing that complex global issues demand integrated approaches that cut across traditional academic boundaries.

The volume features research in areas such as environmental remediation and plant-based solutions, public and environmental health, and the growing role of advanced technologies - including artificial intelligence - in education and medical training. Each chapter presents original insights grounded in empirical research or critical analysis, highlighting practical applications alongside theoretical understanding. Collectively, the contributions illustrate how science and technology can support sustainable development while responding to contemporary societal needs.

A central theme of the book is sustainability as an operational principle rather than a conceptual abstraction. The chapters emphasize responsible innovation, resilience, and long-term impact, demonstrating how scientific and technological tools can be used to protect ecosystems, enhance human well-being, and improve learning and healthcare systems. The book also addresses emerging challenges, ethical considerations, and future directions in applied research.

This book is intended for researchers, academics, postgraduate students, policymakers, and professionals working in science, technology, health, and education. By presenting diverse yet complementary perspectives, it aims to foster interdisciplinary dialogue, inform evidence-based practice, and contribute to ongoing efforts toward a more sustainable and technologically informed future

Contents

The Use and Impact of Modern Technologies in Education and Medical Training	1
Batuhan Selamoglu and Zeliha Selamoglu	
1 Introduction	1
2 Conclusion and Suggestions for the Future	3
References	4
Interaction Between Microplastics-Heavy Metals in Aquatic Ecosystems: Adsorption, Bioaccumulation, and Toxicity	6
Muhammad Waris and Fatma Burcu Karakoç	
1 Introduction	7
2 Microplastic Properties and Heavy Metals Studies	8
3 Environmental Factors Affecting Interaction	8
4 Effects on Bioavailability and Bioaccumulation	9
5 Environmental and Ecosystem-Level Implications	9
6 Ecotoxicological Effects of Metal–Microplastic Interactions	10
7 Mitigation Strategies and Future Directions	10
References	10
Determination of The Level of Atmospheric Pollution by Harmful Substances Formed During the Production of Petroleum Products	13
Dilara Sunakbaeva	
1 Introduction	13
2 Materials and Methods	14
3 Results and Discussion	15
4 Conclusions	16
References	17
The effect of irrigation with industrial wastewater on the anatomical characteristics of the roots of vetiver (Vetiveria zizanioides) as a soil pollution purifier in potted cultivation conditions	19
Sahebe Hajipour, Ebrahim Alinia-Ahandani, Fatma Burcu Karakoç	
1 Introduction	19
2 Materials and Methods	20
3 Results and Discussion	20
4 Conclusion	22
References	22

Water Resources of Kazakhstan: Current State, Utilization, And Management Approaches	24
Dilara Sunakbaeva	
1 Introduction	24
2 Materials and Methods	25
3 Results	26
4 Discussion	27
5 Conclusion	28
References	28

The Use and Impact of Modern Technologies in Education and Medical Training

Batuhan Selamoglu[1-2] and Zeliha Selamoglu[3-4]

Abstract: Artificial intelligence (AI) has emerged as an increasingly useful and reliable tool for various applications, particularly in healthcare. Technology plays a crucial role in shaping human civilization, from ancient inventions like the wheel and printing press to modern innovations like the smart phone and ChatGPT. Actually, the origins of industrial AI date back to the 1950s and the primary target of these primitive systems was for machines to compete human actions. Changes due to Covid-19 are taking place every day, unpredictable, dramatic and fast. The Covid-19 pandemic created a strong urgency for the application of AI in the education and health sectors. This includes automating routine tasks, personalising guest experiences, adjusting pricing strategies, and making your overall operations more efficient. Technology plays a crucial role in shaping human civilization, from ancient inventions like the wheel The global health crisis has brought about significant changes in the realm of employment, necessitating professionals to adjust and demonstrate diverse competencies in order to address emerging needs. The opportunities are plentiful, but so are the challenges. Failing to plan for the current and future challenges could be devastating for global health sectors. This will enable them to adapt and succeed in an ever-changing environment. In this study, how as administrators in the education and medical training, can integrate into the changing world order and the age of artificial intelligence within the scope of education and health sectors, and the challenges they face are discussed and evaluated in every aspect.

Keywords: Artificial intelligence, Covid-19, Health sector, Medical Training

1 Introduction

The declaration of Covid-19 as a pandemic by the World Health Organization on March 11, 2020, prompted professionals around the globe to contemplate what lies ahead. The global health crisis has brought about significant changes in the realm of employment, necessitating professionals to adjust and demonstrate diverse competencies in order to address emerging needs. It has been observed on multiple occasions that an individual and teams who can excel in the face of challenges and view failure as an opportunity and a chance for growth and development tend to

[1] Arel University, Vocational School, Department of Electronics and Automation, Electronics Technology Program, Istanbul, Türkiye
[2] Mersin University, Institute of Science, Electrical and Electronic Engineering, Mersin, Türkiye
[3] Department of Medical Biology, Medicine Faculty, Nigde Omer Halisdemir University, Nigde, Türkiye
[4]Department of Biology, Faculty of Sciences, Khoja Akhmet Yassawi International Kazakh-Turkish University, Turkestan, Kazakhstan

lead to more resilient and prosperous businesses. This will enable them to adapt and succeed in an ever-changing environment. These qualities will be crucial for the success and development of future generations [1].

1.1 Technological Evolution and the Rise of AI in Education

Technology plays a crucial role in shaping human civilization, from ancient inventions like the wheel and printing press to modern innovations like the smart phone and ChatGPT. Imperative study reveals that nearly two-thirds of CEOs believe technology and digital transformation will have the most significant impact on their enterprises' future success. The Digital revolution is causing a significant shift in cognitive or mental work, similar to the Industrial Revolution's transformation of physical work. Relying solely on technology without careful consideration can be a disadvantage rather than an advantage. Choosing the right technology, deep understanding, and using it to perform the required task matters in developing competence [2,3,8].

Artificial Intelligence (AI) is transforming medical education by enhancing pedagogic practices, enhancing learner engagement, and enhancing learning outcomes. Due to AI-based technology improvements such as individualized learning systems, virtual simulation systems, and feedback management software, medical students enjoy improved access to more efficient and interactive learning. Artificial Intelligence (AI) has revolutionized medical education largely through the integration of innovative technologies that enhance learning experience and performance in education. The most important application has been adaptive learning, which applies AI-adaptive learning systems in adapting the learning content based on students' performance [3,9,10].

1.2. Benefits and Challenges of AI Adoption in Medical Training

It enables students to learn specially prepared lessons based on their strengths and weaknesses to enhance learning as well as enhance its effectiveness. Virtual simulation is another successful application of AI, which provides students with the opportunity of scenario-based interactive training without any risk. These simulations enable the replication of the clinical environment and learning medical interventions, enhanced diagnostic skills, and decision-making within the controlled simulated environment. Artificial Intelligence (AI) has introduced a multitude of benefits in medical education that have both improved the educational process for students and teachers. Among its key benefits is increased learning outcomes through adaptive learning techniques. AI-based learning systems track and measure learners, determining their current levels of competency or weaknesses for adaptation [11]. Even with the several advantages of implementing Artificial Intelligence (AI) into medical education, incorporating AI raises many challenges. Many of the critical issues would deal with data privacy and security issues. An educational tool dependent on AI requires massive amounts of student data in order to tailor their learning and report on performance of the students. Faculty training and AI literacy is another pressing challenge. Instructors won't possess the right technical expertise to integrate AI-powered tools into their pedagogies. Without official training and support, there could be a risk of underuse

or misuse of AI technologies [12].

AI-based solutions need to be carefully designed wherein they augment and are not an alternative to prevailing pedagogies. Other challenges in implementing AI in medical education are resistance to change, institutional lack of support, and a stretched budget that require collaboration among teachers, policymakers, and technologists in creating a balanced and effective AI-augmented learning environment [2,13].

Artificial Intelligence (AI) is revolutionizing medical education with increased customized learning, immediate feedback, and simulation-based intensive training in virtual reality. AI not only improves students' engagement and learning rate but also frees instructors from administrative tasks to use their time in mentoring and teaching effectively [14].

Theoretically, AI systems have the capability to supplement deficiencies in medical education and enhance the efficiency of medical education as well as reduce the cost of medical education. All of these issues need to be addressed to achieve the maximum potential promise of AI and ensure safe and ethical practice [15].

2. Conclusion and Suggestions for the future

The future holds the potential that the advancement in AI will ensure that it has more application use in medical education, bringing novel solutions to improvement in learning experiences and practice through teaching. Only when applied responsibly and judiciously will AI lead the medical education into an increasingly adaptive, efficient, and inclusive future [16].

Taking an active approach towards the future is of utmost importance, rather than simply being a passive observer. It is crucial that we promptly take steps to both adapt to the ongoing changes and actively shape the future we will leave behind. By not taking action, there is a possibility that we may allow others to control our future. An additional point to consider is that we can expect uncertainty, ongoing disruption, and perpetual change in our surroundings. The way we decide to respond to this uncertainty is within our control [17].

By cultivating a skill in futures literacy and cultivating a mindset that embraces future thinking, we can enhance our ability to anticipate, strategize, and innovate in order to shape the future we desire. By integrating these skills - futures literacy, adaptability, and resilience - we will possess the necessary tools to embark on this exciting journey of collectively constructing a brighter future. More than ever, it means students must graduate from our systems with a “growth mindset;” a mindset based on 21st Century Skills; Collaboration, Critical Thinking, Communication, Creativity, and Compassion. More than ever, corporations that will thrive in the post-Pandemic world have to become “Learning Organizations.” To face the significant changes caused by the coronavirus, leaders must be flexible and agile and adapt their strategies based on the new situation [6].

In this time of change, administrators of the medical education and health sectors should stick to their core values; core purpose, and their ambitious big, hairy, audacious goals. Of course, they can amend their strategies to match the situation,

but they must always keep their vision in mind. Changes due to Covid-19 are taking place every day, unpredictable, dramatic and fast. They should reevaluate all environmental and competitive forces and either amend their current strategy or adopt a new strategy to realize their goals [5].

2.1. Institutional Resilience and Long-Term Sustainability in Medical Education

During such a quickly-changing and unpredictable environment, leaders must fully understand those changes and their impact on their business and then develop strategies to manage these changes. Regardless, global health sectors must have a strategic plan in place that can be modified in response to the global marketplace, for without sustainable plan many global medical education sectors may not succeed in their current configuration. The opportunities are plentiful, but so are the challenges. Failing to plan for the current and future challenges could be devastating for global universities [4].

References

1. Finstad, G., Giorgi, G., Lulli, L., Pandolfi, C., Foti, G., León-Pérez, J., Cantero-Sánchez, F., & Mucci, N. (2021). Resilience, Coping Strategies and Posttraumatic Growth in the Workplace Following COVID-19: A Narrative Review on the Positive Aspects of Trauma. International Journal of Environmental Research and Public Health, 18. https://doi.org/10.3390/ijerph18189453.
2. Naeem, M. Y., Selamoglu, B., & Selamoglu, Z. (2022). Use of Artificial Machines in Medical Sciences. Eurasian Journal of Medical and Biological Sciences, 2(2), 36-40.
3. Naeem, M. Y., Selamoglu, B., Danebekovna, K. G., Selamoglu, M., & Selamoglu, Z. (2025). The Use and Importance of Artificial Intelligence in Vaccine Research, Development, and Production. Archives of Razi Institute, 80(5), 1103-1112.
4. Shaw, E., Walpole, S., McLean, M., Álvarez-Nieto, C., Barna, S., Bazin, K., Behrens, G., Chase, H., Duane, B., Omrani, O., Elf, M., Guzmán, C., De Barros, E., Gibbs, T., Groome, J., Hackett, F., Harden, J., Hothersall, E., Hourihane, M., Huss, N., Ikiugu, M., Joury, E., Leedham-Green, K., MacKenzie-Shalders, K., Madden, D., McKimm, J., Schwerdtle, P., Peters, S., Redvers, N., Sheffield, P., Singleton, J., Tun, S., & Woollard, R. (2021). AMEE Consensus Statement: Planetary health and education for sustainable healthcare. Medical Teacher, 43, 272 - 286. https://doi.org/10.1080/0142159x.2020.1860207.
5. Schwartz, A., Wilson, J., Boden, S., Moore, T., Bradbury, T., & Fletcher, N. (2020). Managing Resident Workforce and Education During the COVID-19 Pandemic. JBJS Open Access, 5. https://doi.org/10.2106/jbjs.oa.20.00045.
6. Anggraini, A., Sobandi, A., & Groda, S. (2025). Digital Growth Mindset as a Catalyst for Team Collaboration and Communication Skills in Higher Education. Jurnal Inovasi Pendidikan Ekonomi (JIPE). https://doi.org/10.24036/011335560.
7. Naeem, M. Y., Selamoglu, B., Issa, H. Y., & Selamoglu, Z. (2024a). Plasma in medicine and agriculture. In Emerging Applications of Plasma Science in Allied Technologies (pp. 228-242). IGI Global Scientific Publishing.
8. Shanmugasundaram, M., & Tamilarasu, A. (2023). The impact of digital technology, social media, and artificial intelligence on cognitive functions: a review. Frontiers in Cognition. https://doi.org/10.3389/fcogn.2023.1203077.
9. Chan, K., & Zary, N. (2019). Applications and Challenges of Implementing Artificial Intelligence in Medical Education: Integrative Review. JMIR Medical Education, 5. https://doi.org/10.2196/13930.
10. Naeem, M. Y., Selamoglu, B., Sarzhanova, S., & Selamoglu, Z. (2024b). Advancements in Bioprocess Engineering and Plasma: Revolutionizing Medicine Production. In Emerging Applications of Plasma Science in Allied Technologies (pp. 264-284). IGI

Global Scientific Publishing.
11. Mergen, M., Junga, A., Risse, B., Valkov, D., Graf, N., & Marschall, B. (2023). Immersive training of clinical decision making with AI driven virtual patients – a new VR platform called medical tr.AI.ning. GMS Journal for Medical Education, 40. https://doi.org/10.3205/zma001600.
12. Grunhut, J., Marques, O., & Wyatt, A. (2021). Needs, Challenges, and Applications of Artificial Intelligence in Medical Education Curriculum. JMIR Medical Education, 8. https://doi.org/10.2196/preprints.35587.
13. Rincón, E., Jiménez, D., Aguilar, L., Flórez, J., Tapia, Á., & Peñuela, C. (2025). Mapping the use of artificial intelligence in medical education: a scoping review. BMC Medical Education, 25. https://doi.org/10.1186/s12909-025-07089-8.
14. Janumpally, R., Nanua, S., Ngo, A., & Youens, K. (2025). Generative artificial intelligence in graduate medical education. Frontiers in Medicine, 11. https://doi.org/10.3389/fmed.2024.1525604.
15. Paranjape, K., Schinkel, M., Panday, R., Car, J., & Nanayakkara, P. (2019). Introducing Artificial Intelligence Training in Medical Education. JMIR Medical Education, 5. https://doi.org/10.2196/preprints.16048.
16. Lee, H. (2023). The rise of ChatGPT: Exploring its potential in medical education. Anatomical Sciences Education, 17, 926 - 931. https://doi.org/10.1002/ase.2270.
17. Darjee, K., Neupane, P., & Köhl, M. (2023). Proactive Adaptation Responses by Vulnerable Communities to Climate Change Impacts. Sustainability. https://doi.org/10.3390/su151410952

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third-party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

Interaction Between Microplastics-Heavy Metals in Aquatic Ecosystems: Adsorption, Bioaccumulation, and Toxicity

Muhammad Waris[1] and Fatma Burcu Karakoç[2]

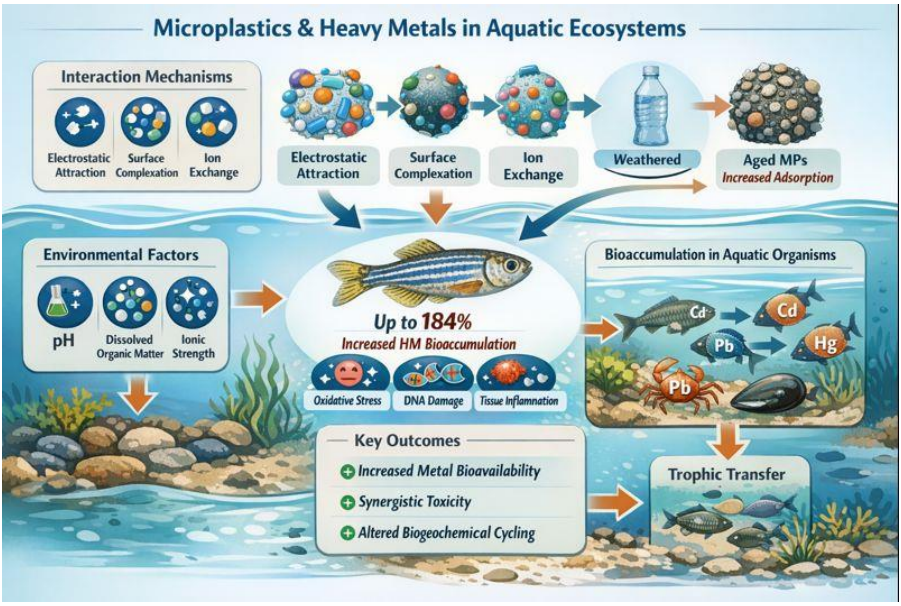
Abstract: Microplastics (MPs) interact with heavy metals (HMs) in aquatic ecosystems through multiple well-characterized physicochemical mechanisms including electrostatic attraction, surface complexation, ion exchange, and hydrogen bonding. MPs adsorb HMs through electrostatic attraction and surface complexation mechanisms, functioning as vectors that increase metal bioavailability and bioaccumulation in aquatic organisms by up to 184%, with interaction strength determined by polymer type (highest in polyethylene and polyvinyl chloride), weathering state, and environmental conditions such as pH and dissolved organic matter. The strength and nature of these interactions depend critically on MPs properties (polymer type, surface chemistry, weathering state) and environmental conditions (pH, dissolved organic matter, ionic strength). Experimental evidence demonstrates that MPs enhance HMs bioaccumulation in aquatic organisms, with cadmium levels increasing 46-184% in zebrafish liver depending on microplastic concentration, and that combined exposure produces synergistic toxic effects including oxidative stress, DNA damage, and tissue inflammation. Polymer-specific differences are substantial: polyethylene and polyvinyl chloride exhibit high adsorption capacity while polyethylene terephthalate shows minimal capacity, and aged microplastics adsorb significantly more metals than pristine materials due to weathering-induced functional groups. At ecosystem scales, these interactions facilitate metal transfer through food webs and alter biogeochemical cycling, though quantitative characterization of trophic transfer remains incomplete.

Keywords: Microplastics, Heavy metals, Adsorption mechanisms, Bioaccumulation, Aquatic ecotoxicology

[1] Department of Environment Science, The Aror University of Art, Architecture, Design and Heritage Sindh, RCW Rohri Bypass, Sukkur, Sindh, Pakistan

[2] Food Processing, Bahçe Vocational School, Osmaniye Korkut Ata University, Osmaniye, Türkiye

Fig: 1. Graphical Abstract



1 Introduction

Microplastics [MPs] and heavy metals [HMs] represent pervasive environmental contaminants in aquatic ecosystems, posing substantial risks to both ecological health and human well-being. The intricate interactions between these two classes of pollutants are drawing increasing attention due to their potential to alter environmental behaviors, bioavailability, and combined toxicity [1]. Research indicates that MPs can act as carriers for HMs, facilitating their transport and enhancing their bioaccumulation within aquatic organisms and subsequent transfer up the food chain. MPs are plastic particles measuring less than 5 mm in diameter, originating from the fragmentation of larger plastic debris or directly from industrial products [2, 3]. Their widespread distribution in various aquatic environments, including oceans, estuaries, lakes, and even deep-sea sediments, highlights a global environmental challenge [4]. Concurrently, HMs are introduced into aquatic systems through industrial, agricultural, and urban activities, accumulating due to their non-biodegradable nature [5]. The co-occurrence of MPs and HMs creates a complex pollution scenario where MPs serve as substrates for HM adsorption, thereby influencing their fate and effects [6]. Multiple physicochemical mechanisms enable MPs to interact with HMs in aquatic environments.

The primary mechanisms identified across studies include electrostatic interactions, complex formation, ion exchange, and surface precipitation. Additional mechanisms documented include surface complexation, hydrogen bonding, hydrophobic interactions, and π–π interactions [Fig. 2] [1]. Langmuir model best described adsorption isotherms, indicating chemical adsorption as the primary

mechanism. The study demonstrated that electrostatic adsorption affinities were inversely related to hydrated ion radius, explaining why Pb^{2+} exhibited higher adsorption capacity due to its smaller hydrated ion radius [7]. Adsorption reached equilibrium within 24 hours, indicating relatively fast kinetics. Surface chemistry played a critical role in metal binding. Spectroscopic techniques including FT-IR, XPS, and NMR identified functional groups like aliphatic, aromatic, hydroxyl, carboxyl, and carbonyl groups on microplastic surfaces [8]. The formation of oxygen-containing functional groups on aged microplastics enhanced metal adsorption compared to pristine materials [9]. It has been observed by SEM and EDS that environmental metals accumulated on microplastic surfaces, with weathering patterns including pits, fractures, and adhering particles [10].

2 Microplastic Properties and Heavy Metals Studies

Studies examined various polymer types, though specific characterization was limited in most reviews. five polymer types, finding significant differences: polyethylene [PE] and polyvinyl chloride [PVC] showed substantial adsorption capacity, while polyethylene terephthalate [PET] demonstrated minimal capacity [11]. The PVC microplastics tested had a mean particle diameter of 150 μm. PE, PET, and PVC polymers, noting that hydrophobic characteristics and large specific surface areas enhanced metal accumulation. Biophysiochemical factors including biofilm formation, crystallinity, and surface charge influenced interactions [12]. Environmental aging modified microplastic surfaces through chemical weathering, creating oxygen-containing functional groups that enhanced metal binding. The studies examined multiple heavy metals with varying properties [13]. EDS spectra revealed differences in elemental types across surface sites, indicating environmental metal accumulation rather than solely inherent contamination [14].

2 Environmental Factors Affecting Interactions

Environmental conditions substantially influenced microplastic-heavy metal interactions through multiple pathways. pH emerged as a critical determinant of adsorption processes [15]. Studies examining pH ranges of 6-8, representative of natural waters, found pH-dependent electrostatic interactions. Changes in pH affected surface charge distribution on microplastics and metal speciation, thereby modulating binding affinity. The electrostatic attraction between negatively charged microplastic surfaces and positively charged metal ions varied with pH, influencing overall adsorption capacity. Dissolved Organic Matter played a major role in metal adsorption dynamics in natural waters [16]. Metal adsorption in waters with high chemical and biological oxygen demands, such as urban wastewater and irrigation water. Ionic strength and salinity affected adsorption through competitive ion effects. Salt ions competed with heavy metal ions for adsorption sites, reducing metal binding at higher ionic concentrations. These parameters, controlled sorption dynamics in both freshwater and marine environments [17]. Additional factors included temperature, which influenced reaction kinetics, and the presence of biofilms on microplastic surfaces. Polymer density, biofilm formation, and agglomeration properties controlled vertical distribution of microplastics in water columns, affecting their spatial exposure to heavy metals [18].

3 Effects on Bioavailability and Bioaccumulation

Microplastics significantly enhanced cadmium accumulation in zebrafish tissues. At 20 μg/L microplastics, cadmium increased by 46% in liver, 10% in gut, and 9% in gills. At 200 μg/L microplastics, accumulation increased dramatically to 184% in liver, 25% in gut, and 46% in gills. The distribution pattern showed gill > gut > liver, indicating differential tissue accumulation [19]. The mechanism involved microplastics releasing adsorbed heavy metals inside organisms after ingestion, thereby increasing metal bioavailability and toxicity [20]. Studies confirmed that bioaccumulation of metal[oid]s desorbed from ingested microplastics significantly influenced pollutant bioavailability to aquatic biota. This vector effect transformed microplastics into carriers that facilitated heavy metal transfer through aquatic food webs [21,24]. Microplastics entered organisms through multiple pathways including direct consumption, gill uptake, cuticle penetration, and cellular translocation. Once internalized, the microplastics acted as localized sources of heavy metal release, creating microenvironments of elevated metal concentration within tissues. Combined exposure to microplastics and heavy metals produced synergistic toxic effects across multiple biological levels [25, 26]. The pattern of tissue damage reflected both direct metal toxicity and indirect effects mediated by microplastic-facilitated metal delivery. Growth and reproductive disorders were documented as consequences of chronic exposure. Beyond physiological effects, exposure altered organism behavior, potentially affecting feeding, predator avoidance, and reproduction. These behavioral modifications could cascade through populations and communities. The mode of toxic action varied by organism type [27].

4 Environmental and Ecosystem-Level Implications

Incorporating bio-accessibility adjustments reduced perceived risk levels compared to total metal content, highlighting the importance of considering bioavailability in human health assessments [28]. At broader scales, microplastic-heavy metal interactions threatened ecosystem structure and function. Effects included shifts in community composition, disruption of food webs, and changes in biogeochemical cycles. These alterations degraded ecosystem services, potentially affecting nutrient cycling, water quality regulation, and habitat provision [1]. The ecotoxicological potential of microplastics varied spatiotemporally as a function of abiotic components [microplastic and heavy metal concentrations, water chemistry] and biotic components [organism sensitivity, community structure] [29]. This complexity necessitated context-specific risk assessments rather than universal predictions. Microplastics influenced heavy metal mobility, fate, and bioavailability in aquatic systems. By altering metal speciation through adsorption/desorption processes, microplastics affected whether metals remained dissolved, particulate-bound, or biologically available [30]. The low desorption capacity observed for some metal-microplastic combinations suggested persistent binding that could facilitate long-range transport or long-term sequestration depending on microplastic fate. The body of evidence reveals consistent findings regarding the capacity of microplastics to interact with heavy metals through well-characterized physicochemical mechanisms, with substantial effects on metal bioavailability and organism toxicity. However, significant heterogeneity exists in

quantitative outcomes, which can be explained through systematic consideration of contextual factors [31].

5 Ecotoxicological Effects of Metal–Microplastic Interactions

The variation in adsorption capacity across polymer types represents genuine material differences rather than methodological artifacts [32]. Aged microplastics consistently showed greater metal adsorption capacity than pristine materials, resolving apparent contradictions between laboratory studies using virgin plastics and field observations of environmental microplastics [33]. Weathering creates oxygen-containing functional groups through chemical oxidation, providing additional binding sites. Studies using fresh plastics may therefore underestimate real-world metal loading, while field-collected microplastics provide more environmentally realistic measurements. This suggests that temporal dynamics matter—newly introduced plastics present lower immediate risk, but accumulating aged plastics pose increasing threat as surface reactivity develops [34,36].

6 Mitigation Strategies and Future Directions

The review suggests that regulatory standards must account for non-linear toxicology—doubling microplastic concentration may quadruple metal bioaccumulation risk rather than merely doubling it. While individual studies documented bioaccumulation in specific organisms, the ecosystem-level consequences remain incompletely characterized. The recognition that microplastics facilitate metal transfer through food webs implies potential for biomagnification, but quantitative data on trophic transfer factors are absent from the reviewed literature. Addressing the combined pollution of MPs and HMs requires a multi-faceted approach. Understanding the adsorption mechanisms and influencing factors is crucial for developing effective mitigation strategies. Predictive models, including machine learning and deep learning approaches, are being employed to unravel the complex adsorption behaviors and mechanisms, especially given the variability in MP properties, HM species, and environmental conditions. Further research is needed to: Standardize methodologies for quantifying MP-HM interactions to allow for better cross-study data synthesis. Investigate the long-term ecological consequences of MP-HM co-pollution, moving beyond individual adverse effects. Explore the effects of aging and weathering on microplastics, as these processes can alter surface properties and, consequently, HM adsorption capacity. Develop novel materials or techniques for the removal of MPs and HMs from aquatic environments. Assess the activation phenomena and mechanisms of HMs in soil in the presence of microplastics, as many studies have primarily focused on aquatic systems.

References

1. Narwal N, Kakakhel MA, Katyal D, Yadav S, Rose PK, Rene ER, et al. Interactions between microplastic and heavy metals in the aquatic environment: Implications for toxicity and mitigation strategies. Water, Air, & Soil Pollution. 2024;235[9]:567.
2. Cverenkárová K, Valachovičová M, Mackuľak T, Žemlička L, Bírošová L. Microplastics in the food chain. Life. 2021;11[12]:1349.
3. Mesut S. Blue economy and blue Ocean strategy. J Ecol Nat Resour. 2021; 5:000263.

4. Callender E. Heavy metals in the. Environmental geochemistry. 2005;9[67].
5. Jadaa W, Mohammed H. Heavy metals–definition, natural and anthropogenic sources of releasing into ecosystems, toxicity, and removal methods–an overview study. Journal of Ecological Engineering. 2023;24[6]:249–71.
6. Qin Y, Tian X, Zhang J, Tu Y, Chen C. Combined toxicity and ecological impacts of soil microplastics and heavy metals in rhizosphere microenvironments: A comprehensive review. Journal of Soils and Sediments. 2025;25[9]:2551–70.
7. Lan Q, Bassi AS, Zhu J-XJ, Margaritis A. A modified Langmuir model for the prediction of the effects of ionic strength on the equilibrium characteristics of protein adsorption onto ion exchange/affinity adsorbents. Chemical Engineering Journal. 2001;81[1-3]:179–86.
8. Luo H, Tu C, Liu C, Zeng Y, He D, Zhang A, et al. Probing the molecular interaction between photoaged polystyrene microplastics and fulvic acid. Science of The Total Environment. 2024; 920:170933.
9. Jian W, Chen L, Cui Y, Shao H, Wu M. Dynamic transformation of oxygen-containing functional groups in aged PVC microplastics: Governing composite pollutant formation and environmental remediation. Journal of Water Process Engineering. 2025; 77:108517.
10. Aghilinasrollahabadi K, Salehi M, Fujiwara T. Investigate the influence of microplastics weathering on their heavy metals uptake in stormwater. Journal of hazardous materials. 2021; 408:124439.
11. Du H, Zhang Y, Jiang H, Wang H. Adsorption of rhodamine B on polyvinyl chloride, polystyrene, and polyethylene terephthalate microplastics in aqueous environments. Environmental Technology & Innovation. 2022; 27:102495.
12. Adeleye AT, Bahar MM, Megharaj M, Fang C, Rahman MM. The unseen threat of the synergistic effects of microplastics and heavy metals in aquatic environments: a critical review. Current Pollution Reports. 2024;10[3]:478–97.
13. Huang W, Jiang G, Xie L, Chen X, Zhang R, Fan X. Effect of oxygen-containing functional groups on the micromechanical behavior of biodegradable plastics and their formation of microplastics during aging. Journal of Hazardous Materials. 2024; 463:132911.
14. Wu S, Zhang X, Sun Y, Wu Z, Li T, Hu Y, et al. Transformation and immobilization of chromium by arbuscular mycorrhizal fungi as revealed by SEM–EDS, TEM–EDS, and XAFS. Environmental Science & Technology. 2015;49[24]:14036–47.
15. Fang S, Hua C, Yang J, Liu F, Wang L, Wu D, et al. Combined pollution of soil by heavy metals, microplastics, and pesticides: Mechanisms and anthropogenic drivers. Journal of Hazardous Materials. 2025; 485:136812.
16. Bhaumik S, Chakraborty P. Interactions between microplastics [MPs] and trace/toxic metals in marine environments: Implications and insights—A comprehensive review. Environmental Science and Pollution Research. 2024;31[50]:59681–99.
17. Le B-N, L. Nguyen A, Ngo T, Duong T-L, Nguyen T-V, Nguyen P-A, et al. Application of biosensor for determination of biochemical oxygen demand and heavy metal toxicity in urban canal water. International Journal of Environmental Science and Technology. 2024;21[10]:7307–20.
18. Qin Y, Tu Y, Chen C, Wang F, Yang Y, Hu Y. Biofilms on microplastic surfaces and their effect on pollutant adsorption in the aquatic environment. Journal of Material Cycles and Waste Management. 2024;26[6]:3303–23.
19. Lu K, Qiao R, An H, Zhang Y. Influence of microplastics on the accumulation and chronic toxic effects of cadmium in zebrafish [Danio rerio]. Chemosphere. 2018; 202:514–20.
20. Al Marshoudi M, Al Reasi HA, Al-Habsi A, Barry MJ. Additive effects of microplastics on accumulation and toxicity of cadmium in male zebrafish. Chemosphere. 2023; 334:138969.
21. McHale ME, Sheehan KL. Bioaccumulation, transfer, and impacts of microplastics in aquatic food chains. Journal of Environmental Exposure Assessment. 2024;3[3]:N/A–N/A.
22. Liaqat S, Hussain M, Riaz J. Entry of the microplastics in food chain and food web. Microplastic Pollution: Springer; 2024. p. 289–306.
23. Selamoglu M. Importance of the cold chain logistics in the marketing process of aquatic products: An update study. Journal of Survey in Fisheries Sciences. 2021;8[1]:25–9.
24. Selamoglu M. The effects of the Ports and water transportation on the Aquatic ecosystem. Op Acc J Bio Sci & Res. 2021;10[1]:2021.
25. Oros A. Bioaccumulation and trophic transfer of heavy metals in marine fish: Ecological and ecosystem-level impacts. Journal of Xenobiotics. 2025;15[2]:59.

26. Shah S, Kumar A. Bioavailability, bioconcentration, and biomagnification of pollutants. Environmental toxicology and ecosystem: CRC Press; 2022. p. 179–214.
27. Tang KHD. Combined Toxicity of Microplastics and Antimicrobials on Animals: A Review. Antibiotics. 2025;14[9]:896.
28. Dean JR, Amaibi PM, Okorie A, Entwistle JA. A critical evaluation of the use and 'misuse'of As and Pb bioaccessibility data in human health risk assessments. Environmental Research. 2020; 189:109915.
29. Yang D, Hou Y, Wei C, Ling J, Zheng X. Aquatic Microcosms in Ecotoxicology: The Community-Level Ecological Risk Assessment of Pollutants. Toxics. 2025;13[8]:694.
30. Liu G, Dave PH, Kwong RW, Wu M, Zhong H. Influence of microplastics on the mobility, bioavailability, and toxicity of heavy metals: a review. Bulletin of Environmental Contamination and Toxicology. 2021;107[4]:710–21.
31. Xie Y, Irshad S, Jiang Y, Sun Y, Rui Y, Zhang P. Microplastic-mediated environmental behavior of metal contaminants: mechanism and implication. Environmental Science and Pollution Research. 2024;31[31]:43524–39.
32. Elert AM, Becker R, Duemichen E, Eisentraut P, Falkenhagen J, Sturm H, et al. Comparison of different methods for MP detection: what can we learn from them, and why asking the right question before measurements matters? Environmental Pollution. 2017; 231:1256–64.
33. Xie M, Huang J-L, Lin Z, Chen R, Tan Q-G. Field to laboratory comparison of metal accumulation on aged microplastics in coastal waters. Science of the Total Environment. 2021; 797:149108.
34. Fan Q, Sun J, Chu L, Cui L, Quan G, Yan J, et al. Effects of chemical oxidation on surface oxygen-containing functional groups and adsorption behavior of biochar. Chemosphere. 2018; 207:33–40.
35. Deline AR, Frank BP, Smith CL, Sigmon LR, Wallace AN, Gallagher MJ, et al. Influence of oxygen-containing functional groups on the environmental properties, transformations, and toxicity of carbon nanotubes. Chemical reviews. 2020;120[20]:11651–97.
36. Shu X, Yang M, Lin H, Zhang Q, Zhang L, Liu J, et al. Oxalic-activated minerals enhance the stabilization of polypropylene and polyamide microplastics in soil: Crucial roles of mineral dissolution coupled surface oxygen-functional groups. Science of The Total Environment. 2023; 875:162563.

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

Determination of The Level of Atmospheric Pollution by Harmful Substances Formed During the Production of Petroleum Products

Dilara Sunakbaeva[1]

Abstract: The production of petroleum products is accompanied by the emission of significant quantities of harmful substances that have a complex impact on atmospheric air, climate, and human health. The main sources of pollution include technological processes of oil refining, transportation, storage, and combustion of raw materials. This paper analyzes the current state of air pollution in areas surrounding oil refineries and identifies the key categories of emissions—sulfur oxides (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs).

Special attention is paid to modern monitoring methods, including the use of next-generation gas analyzers, gas chromatography-mass spectrometry (GC/MS), satellite remote sensing systems (Sentinel-5P, NASA MODIS), and atmospheric dispersion modeling (AERMOD, CALPUFF). The paper presents approaches to the digitalization of environmental monitoring and the application of artificial intelligence technologies for predicting emissions and assessing environmental risks.
The influence of industrial emissions on microclimate change, vegetation degradation, and the formation of secondary pollutants such as photochemical smog and tropospheric ozone is also discussed. The study highlights the importance of transitioning the oil refining industry toward sustainable, carbon-neutral, and resource-efficient technologies that comply with international environmental standards (ISO 14001, ESG).

The presented results contribute to improving environmental monitoring systems and developing strategies to reduce the negative impact of oil refining on the environment.

Keywords: atmospheric pollution, oil refining, harmful substances, emissions, monitoring, ecology, carbon neutrality, sustainable development

1 Introduction

The problem of atmospheric pollution resulting from the production and processing of petroleum products remains one of the most pressing environmental challenges

[1] Khoja Akhmet Yassawi International Kazakh-Turkish University, Faculty of Natural Sciences, Department of Ecology and Chemistry, Turkestan, Kazakhstan

of modern times. According to the World Health Organization, more than 90% of the global population breathes air contaminated with harmful substances exceeding acceptable concentrations [1]. A significant share of these pollutants originates from oil refining and petrochemical industries, which emit sulfur oxides, nitrogen oxides, carbon oxides, volatile organic compounds (VOCs), and polycyclic aromatic hydrocarbons [2].

Oil extraction, transportation, and refining processes generate a considerable amount of gaseous and solid pollutants. According to the IEA Energy and Air Pollution 2023 report, oil refineries contribute up to 15% of total industrial emissions to the atmosphere [3]. In Kazakhstan, the highest levels of air pollution are recorded in regions with major refineries—Atyrau, Pavlodar, and Shymkent—where exceedances of sulfur dioxide, nitrogen oxides, soot particles, and hydrocarbons have been observed [4].

Modern global research focuses on developing technologies that can reduce harmful emissions and minimize environmental impact. These include:

- implementation of catalytic and thermal afterburning systems for exhaust gases;
- adoption of closed-loop refining and vapor recovery cycles;
- application of carbon capture, utilization, and storage (CCUS) technologies;
- digitalization of environmental monitoring using satellite systems and artificial intelligence [5].

In the EU, China, and the USA, large-scale environmental modernization programs are being introduced to achieve carbon-neutral production by 2050. Kazakhstan is also moving in this direction, implementing its National Air Quality Strategy 2030 (2024) [4].

Thus, determining the level of atmospheric pollution by harmful substances during petroleum production is not only a scientific and research priority but also a strategic direction of national environmental policy. The goal of this study is to assess the scale of atmospheric pollution caused by oil refining, identify the main sources and composition of emissions, and analyze modern monitoring methods and strategies for reducing their adverse effects.

2 Materials and Methods

A comprehensive approach was applied to assess the degree of atmospheric pollution in areas surrounding oil refineries, integrating modern instrumental, laboratory, and remote monitoring methods.

Instrumental observations were carried out using automated air quality control stations and portable gas analyzers, providing real-time measurements of sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs) [4]. These systems enabled continuous tracking of air quality parameters and detection of short-term exceedances of permissible limits.

Laboratory studies involved gas chromatography–mass spectrometry (GC/MS), ensuring precise identification of hydrocarbons, polycyclic aromatic compounds, and other petroleum-derived toxicants [5].

Remote monitoring was conducted using satellite data from Sentinel-5P and NASA MODIS, which allowed for the spatial and temporal analysis of emission patterns and their correlation with industrial activity [6].

Atmospheric modeling was performed using AERMOD and CALPUFF dispersion models, which take into account meteorological conditions, terrain, and emission sources. These models provided the capability to forecast pollutant concentrations in surface air layers and identify potential high-risk zones [7].

A comparative overview of the applied monitoring methods and their analytical capabilities is presented in Table 1, which substantiates the choice of optimal approaches for analyzing the spatial and temporal dynamics of atmospheric pollution.

Table 1. Modern Methods for Monitoring Atmospheric Pollution During Petroleum Production

№	Method / Instrument	Main Capabilities	Advantages
1.	Gas analyzers and automatic monitoring stations	Measurement of SO_2, NO_x, CO, and VOC concentrations in real time	High accuracy and capability for continuous monitoring
2.	Gas chromatography–mass spectrometry (GC/MS)	Determination of the composition and concentrations of organic pollutants	High sensitivity and specificity
3.	Satellite environmental monitoring (Sentinel-5P, NASA MODIS)	Analysis of spatial distribution of pollutants and emission dynamics	Wide territorial coverage, independence from ground measurements
4.	Atmospheric dispersion models (AERMOD, CALPUFF)	Prediction of pollutant concentrations and dispersion of emissions	Ability to simulate pollution scenarios

3 Results and Discussion

The results of the comprehensive observations indicate that pollutant concentrations in areas near oil refineries often exceed national and international air quality standards [8]. The most significant emissions include nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), and volatile organic compounds (VOCs), which form stable pollution zones around production sites.

Nitrogen oxides (NO_x) are among the most widespread pollutants in oil refining areas. They actively participate in photochemical reactions, forming secondary aerosols and smog, thereby deteriorating air quality and affecting human health [9].

Sulfur dioxide (SO_2), generated during the combustion of sulfur-containing petroleum products, contributes to acid rain formation, vegetation damage, and material corrosion [10].

Volatile organic compounds (VOCs), such as benzene, toluene, and xylene, are carcinogenic and play a major role in the formation of tropospheric ozone — a key component of photochemical smog [11].
Modern research confirms that reducing anthropogenic load is possible through the implementation of innovative technologies and environmental management systems [12]. The most effective measures include:

- catalytic and thermal oxidation of VOCs,
- installation of vapor recovery units (VRU),
- adoption of closed-loop processes and low-emission catalysts [13–14].

In recent years, special attention has been given to the digitalization of environmental monitoring. Artificial intelligence (AI) and machine learning technologies are increasingly used to predict pollutant concentrations and optimize emission control systems in real time, improving the efficiency of environmental management [15].

Table 2 presents a comparative summary of the main pollutants and their environmental and health effects, while Table 3 outlines modern technological solutions aimed at reducing emissions in the petroleum refining industry.

Table 2. Major Atmospheric Pollutants and Their Effects

№	Pollutant	Environmental Impact	Health Effects
1.	Nitrogen oxides (NO_x)	Formation of photochemical smog and secondary aerosols	Respiratory irritation, asthma
2.	Sulfur dioxide (SO_2)	Acid rain, vegetation damage	Respiratory diseases
3.	Volatile organic compounds (VOCs)	Formation of tropospheric ozone, carcinogenicity	Effects on the central nervous system, cancer

Table 3. Modern technologies for reducing emissions in the petroleum refining industry

Technology	Principle of operation	Environmental effect	Example of application
Catalytic oxidation	Oxidation of VOCs and CO at high temperatures using noble metal catalysts	Reduction of VOC and CO emissions	Refinery gas treatment units
Vapor Recovery Units (VRU)	Capture and condensation of hydrocarbon vapors from storage and loading operations	90–98% reduction in VOC losses	Oil storage terminals
Closed-loop systems	Recirculation of process gases and recovery of hydrocarbons	Minimization of emissions and energy loss	Distillation and cracking processes
Carbon Capture and Storage (CCS)	Absorption and sequestration of CO_2 from flue gases	Decrease in greenhouse gas emissions	Hydrogen production units
Digital emission monitoring	Use of AI-based control systems for real-time emission tracking	Early detection and reduction of peak emissions	Smart refinery management systems

Overall, the analysis shows that sustainable development of the oil refining sector is achievable only through a comprehensive combination of engineering, analytical, and digital approaches aimed at minimizing anthropogenic impact and preserving air quality.

4 Conclusion

Assessing atmospheric pollution levels in petroleum production areas is a crucial component of environmental safety in industrial regions. The results demonstrate that oil refineries remain among the primary sources of sulfur, nitrogen, carbon, and particulate emissions that have long-term effects on the atmosphere, climate, and human health [16].

Integration of automated environmental monitoring systems capable of real-time emission detection and dispersion forecasting plays a vital role in mitigating pollution

[17]. Such systems, based on Internet of Things (IoT), artificial intelligence (AI), and satellite sensing technologies, are already used in the EU, USA, China, and Kazakhstan for emission analysis and health risk assessment [18].

Current research emphasizes the transition to low-carbon and waste-free oil refining technologies, the use of next-generation catalysts, carbon capture and storage systems (CCS/CCUS), and biotechnological methods for land restoration [19]. The development of carbon-neutral strategies in the petrochemical industry aligns with the UN Sustainable Development Goals (SDGs 7, 13, and 15).

For Kazakhstan and Central Asia, key priorities include:

- improving the national air quality monitoring system;
- implementing international industrial emission standards;
- increasing environmental responsibility in the oil and gas sector.
- advancing interdisciplinary research in “green chemistry” and “clean energy” [20].

Thus, reducing the negative environmental impact of oil refining is possible only through the integration of scientific innovation, effective state regulation, and environmental education. The application of modern technologies, international cooperation, and digital tools provides a real foundation for the development of a sustainable and environmentally safe oil industry of the future.

References

1. European Environment Agency (EEA). Air pollution sources and impacts. 2023.
2. World Health Organization (WHO). Ambient Air Pollution: A Global Assessment of Exposure and Burden of Disease. Geneva, 2022.
3. Chen Y. et al. Air Pollution from Oil Refining and its Health Effects. Environmental Research, 2023.
4. Kazemi, M., et al. Advanced Air Monitoring Technologies in Petroleum Industry. Journal of Environmental Engineering, 2024.
5. Li, X. et al. Chromatographic Analysis of Volatile Organic Compounds in Industrial Emissions. Atmospheric Chemistry and Physics, 2023.
6. NASA MODIS Satellite Data. Global Atmospheric Composition Monitoring. 2024.
7. US EPA. AERMOD User’s Guide. 2023.
8. Al-Ghamdi, S. et al. Assessment of Air Quality Around Oil Refineries. Environmental Pollution, 2022.
9. Zhang, T. et al. Formation of Secondary Aerosols from NOx Emissions in Industrial Zones. Atmospheric Environment, 2023.
10. World Meteorological Organization (WMO). Global Sulfur Emissions Report. 2023.
11. IARC. Volatile Organic Compounds and Cancer Risk. 2022.
12. Luo, Q. et al. Catalytic Oxidation of VOCs: Recent Advances. Applied Catalysis B: Environmental, 2024.
13. OECD. Recovery and Recycling Technologies in Oil Refining. 2024.
14. Xu, L. et al. Green Catalysts in Petroleum Processing. Journal of Cleaner Production, 2023.
15. Wang, H. et al. AI-based Air Quality Prediction in Industrial Areas. Environmental Modelling & Software, 2024.
16. UNEP. Towards Carbon-Neutral Oil Refining. United Nations Environment Programme, 2024.
17. European Commission. Industrial Emissions and Air Quality Monitoring Strategies in the EU. Brussels, 2023.
18. Liu, J. et al. Artificial Intelligence Applications in Air Quality Monitoring. Environmental Science & Technology, 2024.
19. BP Energy Outlook. Decarbonizing the Refining Sector: Pathways and Technologies. 2024.
20. Ministry of Ecology and Natural Resources of the Republic of Kazakhstan. National Air Quality Strategy 2030. Astana, 2024.

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

The effect of irrigation with industrial wastewater on the anatomical characteristics of the roots of vetiver (*Vetiveria zizanioides*) as a soil pollution purifier in potted cultivation conditions

Sahebe Hajipour[1] Ebrahim Alinia-Ahandani[2] and Fatma Burcu Karakoç[3]

Abstract: Today, with the increase in the world population and the subsequent development of industries and factories, the amount of wastewater entering the environment, which often contains heavy metals and various other pollutants, is increasing. In the process of environmental purification, plants have the ability to absorb heavy metals and can absorb these pollutants from soil and water and store them in their roots and aerial organs. In this regard, in order to investigate the absorption of heavy metals by the roots of vetiver plants and to examine the anatomical changes in the roots, an experiment was conducted using vetiver plants in a completely randomized design with three replications. Plants treated with industrial wastewater and control plants were irrigated with urban water. After a six-month experimental period, anatomical studies were conducted on plants treated with industrial wastewater and control plants. The results of root studies in control and treated plants showed that the root diameter, central cylinder diameter, and number of vascular bundles in treated plants increased compared to the control. Overall, the results of this study showed that in the process of heavy metal absorption, changes are also made in some anatomical traits of the treated plants, which can help increase the plant's resistance in a polluted environment.

Keywords: Industrial wastewater, phytoremediation, vetiver plant, heavy metals, soil pollution

1 Introduction

Today, water quality has declined due to various pollutants, making it difficult to use water for consumption and other purposes. Water pollution is caused by the introduction of many undesirable chemical compounds into water systems. Compared to physical methods of soil purification, phytoremediation has many advantages and can also minimize environmental disturbance [1]. The term phytoremediation is defined as the use of plants to remove or eliminate hazardous pollutants from water, soil, and air (2-4).

[1] 1Department of Plant Biology, Faculty of Basic Sciences, Golestan University, Gorgan, Iran
[2]Food and Drug Research Center, Food and Drug Administration, Military of Health and Medical Education, Tehran, Iran
[3] Food Processing, Bahçe Vocational School, Osmaniye Korkut Ata University, Osmaniye, Türkiye

Vetiver (Vetiveria zizanioides (L.)) is a herbaceous, perennial plant with high ecological adaptability, and is mainly native to India and grows to more than 150 cm. Vetiver belongs to the Poaceae family and the Andropogoneae tribe. The leaves of this plant grow 120 to 150 cm. The root system of vetiver has a very strong structure and can grow 3 to 4 meters during the first year. The ability of vetiver to absorb heavy metals, nitrates, and phosphates in wastewater has also attracted attention in many countries around the world [5]. The aim of this study was to investigate the absorption of some heavy metals in industrial wastewater by vetiver and its effect on some anatomical characteristics of vetiver roots.

2 Materials and Methods

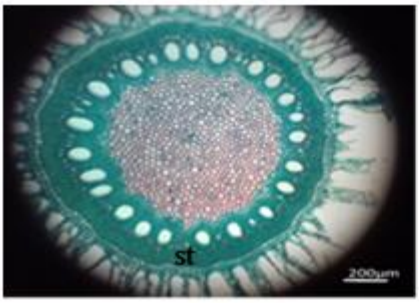
35 kg of soil was collected to a depth of 34 cm from the Safra-Pascha area of Asthaaneh, Ashrafieh, Gilan Province and was first sieved to obtain a uniform texture. 24 vetiver plants were separated from the mother plant at the plant division area. Each pot was filled with 8 kg of sieved soil and 3 vetiver plants of approximately equal weight were planted in each pot. The prepared pots were immediately watered to fill the gaps between the soil and the roots. The pots were watered with municipal water twice a week for one month from the time of planting, 200 ml each time, until the plants reached a relative growth. From the second month, as the temperature increased, the control pots were watered with 500 ml of municipal water and the treatment pots with 500 ml of industrial wastewater, twice a week, and this process of watering the control and treatment pots continued for 6 months. After the 6-month experimental period, the concentration of heavy metals in the soil contaminated with industrial wastewater and the roots of vetiver plants was measured using an ICP device [5]. In order to evaluate the vegetative structure of the plants and their relationship with the rate of heavy metal purification, the roots of vetiver plants were collected from the control and treated pots after the end of the treatment period. The anatomical structure of the roots of the control and treated plants was examined by preparing thin sections manually using a NIKON light microscope [6,7].

3 Results and Discussion

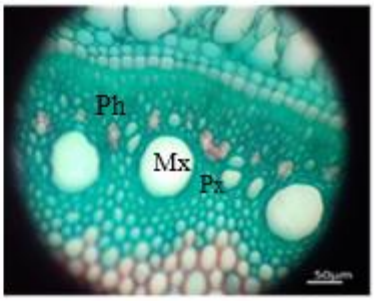
According to Figure 1, it was observed that during six months of irrigation with industrial wastewater, the amount of zinc accumulation in the roots of treated plants increased compared to control plants, and this difference was significant. In a study on vetiver plants, treated plants that were irrigated with hospital wastewater containing heavy elements had the highest zinc accumulation in the roots of the plant [8]. The higher accumulation of heavy metals in the roots compared to the shoots indicates the plant's tolerance mechanism to high concentrations of heavy metals in the soil [9]. According to Figure 2, it was observed that during six months of irrigation with industrial wastewater, the amount of chromium accumulation in the roots of treated plants increased compared to the control, and this difference was significant. Reports indicate that chromium accumulates mainly in the roots, and the reason for this is that chromium becomes immobile in the vacuoles of root cells [11].

Table 1: Examination of anatomical (quantitative) traits of vetiver roots (diameter in µm). The * symbol indicates the significance of the traits in relation to each other (Ph: phloem, MX: metaxylem, PX: protoxylem, St: central cylinder).

Treatment	Control	Trait type	Row
*4308/8±125/2	2888/7±30/09	Root diameter	1
*2713/4±154/2	773/6±41/9	Central cylinder diameter	2
*19/9±3/27	11/4±0/86	Protoxylem diameter	3
*100/01±2/05	70/32±3/18	Metoxylem diameter	4
23-25	14-16	Number of vascular bundles	5

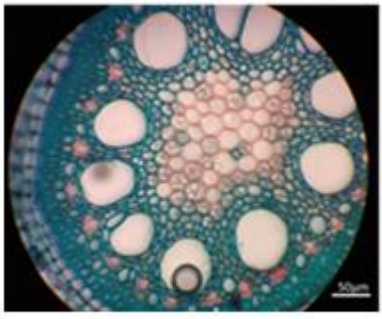


2

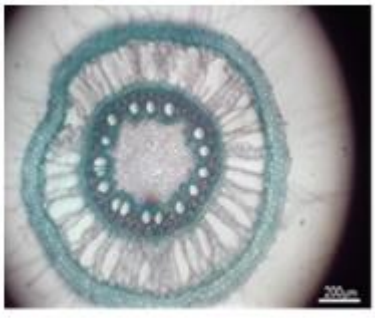


1

Figure 1: Anatomy of vetiver roots treated with industrial wastewater. Magnification 40× Figure 2: Anatomy of vetiver roots treated with industrial wastewater. Magnification 10×



3



4

Figure 3: Root anatomy of the control vetiver plant. Magnification 40× Figure 4: Root anatomy of the control vetiver plant. Magnification 10×

According to Table 1 and Figures 1 to 4, the results of the analysis of anatomical traits of treated and control plants using Image J software showed that the root diameter and central cylinder diameter increased in treated plants compared to control plants, and the number of vascular bundles increased in treated plants compared to control. The root epidermis protects internal tissues from damage with its protective role, and also plays an important role in controlling water within the plant [12]. Beneath the epidermis, the hypodermis layer, which consists of one to two layers of cells, is located. The cortex, which consists of aerated parenchyma tissue, is located below the hypodermis. The cortex region is a part of the root that acts as a storage site for water and nutrients. The pericarp is seen as the first layer of the central cylinder of the root under the endoderm layer, which acts as the origin of lateral roots in plants. In the central cylinder of the vetiver root, due to the monocotyledonous nature of the plant, there were a large number of xylem bundles that were interspersed with phloem bundles. In the present study, the increase in the number of vascular bundles, the diameter of the vascular system, and the increase in root diameter could be due to the relative resistance of the treated plants to the elements in the effluent, which resulted in an increase in the diameter and number of wood elements (protoxylem and metaxylem), because xylems are responsible for the transport of minerals, and on the other hand, it could be an indication of the positive effect of zinc on the treated plants. Since zinc is also involved in photosynthetic processes, by increasing the concentration of chlorophylls, it increased photosynthesis and, subsequently, photosynthetic products, which are transported by phloems, and as a result, increased the compounds in the phloem tissue. Reports show that heavy metals have different effects on the root anatomy of different plants, and the absorption and accumulation of metals at high concentrations leads to structural and substructural changes in the roots of various plants [13].

Phytoremediation is a cost-effective and environmentally friendly method in which plants use their natural abilities to purify the environment. We also have had many methods to find using the plants as a nice agent to upgrade the human health [14,17].

Conclusion

As a plant-based technology, the success of phytoremediation inherently depends on the selection of the appropriate plant. Changes in the root anatomy of plants treated with industrial wastewater compared to the control showed that vetiver can resist heavy metals through changes in anatomical traits while absorbing heavy metals present in wastewater.

References

1. Girija, N., Nair, M.M., Lakshmi, S. and Pillai, S.S., 2016. Phytoremediation potential of Vetiver zizanioides: a green technology to remove pollutants from Pampa River by hydroponic technique. Indian Journal of Advances in Chemical Science, 4(4), pp.464-468.
2. 2.Karami, A. and Shamsuddin, Z.H., 2010. Phytoremediation of heavy metals with several efficiency enhancer methods. African Journal of Biotechnology, 9(25), pp.3689-3698

3. Mesut, S. (2021). Blue economy and blue Ocean strategy. J. Ecol. Nat. Resour, 5, 000263.
4. Selamoglu, M. (2021). The effects of the Ports and water transportation on the Aquatic ecosystem. Op Acc J Bio Sci & Res, 10(1), 2021.
5. Bazobandi, Mohammad, Hadizadeh, Mohammad Hassan, Arin, Hadi. (2012), "Efficiency of narrow-leaved herbicides and glyphosate in chemical control of vetiver (Vetiveria zizanioides (L.) Nash)." Weed Research, No. 1, pp. 72-61.
6. Hajipour, S., Alinia-Ahandani, E., & Selamoglu, Z. (2023). Heavy metals in livestock products (milk and red meat). Cornous Biology, 1(3), 1-4.
7. Bercu, R. and Jianu, L.D., 2003. Practicum de Morphology și anatomia plantelor. Ovidius University Press
8. Hajipour, S., Mohammadi Deylamani, M., Momen Zadeh, M., & Afshar Mohammadian, M. (2022). Purification of some industrial waste water contaminants entering the Caspian Sea basin using vetiver plant. Advanced Environmental Sciences, 20(3), 191-210.
9. Brunetti, G., Farrag, K., Rovira, P.S., Nigro, F. and Senesi, N., 2011. Greenhouse and field studies on Cr, Cu, Pb and Zn phytoextraction by Brassica napus from contaminated soils in the Apulia region, Southern Italy. Geoderma, 160(3-4), pp.517-523.
10. Shanker, A.K., Cervantes, C., Loza-Tavera, H. and Avudainayagam, S., 2005. Chromium toxicity in plants. Environment international, 31(5), pp. 739-753.
11. Saleem, M.Y., Mirza, J.I. and Haq, M.A., 2010. Combining ability analysis of some morpho-physiological traits in Basmati rice. Pakistan Journal of Botany, 42(5), pp. 3113-3123.
12. Alinia-Ahandani, E., Malekirad, A. A., Nazem, H., Fazilati, M., Salavati, H., & Rezaei, M. (2021). Assessment of SOME TOXIC METALS in Ziziphora (Ziziphora persica) obtained from local market in Lahijan, Northern Iran. Ann Mil Health Sci Res, 19(4), e119991.
13. Alinia-Ahandani, E., Fazilati, M., Boghozian, A., & Alinia-Ahandani, M. (2019). Effect of ultraviolet (UV) radiation bonds on growth and chlorophyll content of Dracocephalum moldavica L herb. J. Biomol. Res. Ther, 8(1), 1-4.
14. Hajipour, S., Alinia-Ahandani, E., Behnaz, S. B., Zahra, A. T., Selamoglu, Z., & Akram, M. (2023). Phytoremediation potential and its methods-a review. Bioengineering Studies, 4(1), 1-8.
15. Alinia-Ahandani, E., Rafeie, F., Alizadeh-Tarpoei, Z., Hajipour, S., Selamoglu, Z., & Arici, E. C. A. (2023). Overview on raspberry leaves and cohosh (Caulophyllum thalictroides) as partus preparatory. Central Asian Journal of Plant Science Innovation, 2(2), 54-61.
16. Daglia, M., Pasdaran, A., Ahandani, E. A., & Selamoglu, Z. (2023). Medicinal plants as a hopeful therapeutic approach against COVID-19 infection. Central Asian Journal of Medical and Pharmaceutical Sciences Innovation, 1(3), 1.
17. Alinia-Ahandani, E., Boghozian, A., & Alizadeh, Z. (2019). New approaches of some herbs used for reproductive issues in the world: Short review. J Gynecol Women's Health, 16(1), 555927.

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

Water Resources of Kazakhstan: Current State, Utilization, And Management Approaches

Dilara Sunakbaeva[1]

Abstract: Kazakhstan, the largest landlocked country in Central Asia, possesses diverse and strategically important water resources that play a crucial role in agriculture, industry, and energy production. However, uneven spatial distribution, transboundary dependence, and climate-induced variability have made water management a key environmental and economic challenge. This review analyzes the current state of Kazakhstan's surface and groundwater resources, examines the major river basins such as the Syr Darya, Ili, Irtysh, and Ural, and evaluates their ecological and economic significance. The study also reviews water utilization in agriculture, hydropower, and municipal sectors, highlighting issues of water scarcity, pollution, and inefficient irrigation systems. Modern approaches to water resource management, including integrated water resource management (IWRM), digital monitoring, and sustainable transboundary cooperation, are discussed. The article emphasizes the need for coordinated policies, technological modernization, and regional collaboration to ensure sustainable water use and climate resilience in Kazakhstan.

Keywords: Kazakhstan, water resources, water management, irrigation, transboundary rivers, sustainability, climate change, integrated water resource management

1 Introduction

Kazakhstan's water resources play a vital role in sustaining agricultural productivity, industrial growth, and ecosystem stability across Central Asia. Despite the country's vast territory, its water availability per capita is among the lowest in the region, primarily due to uneven geographic distribution and transboundary dependency. Over 45% of Kazakhstan's renewable water resources originate outside its borders, particularly from China, Uzbekistan, and Kyrgyzstan [1].

Climate change, increasing demand from the agricultural sector, and the degradation of irrigation infrastructure further exacerbate water scarcity. According to the Ministry of Ecology and Natural Resources [1], the total volume of renewable water resources in Kazakhstan is estimated at approximately 100 km³ per year, but only 56–60 km³ are effectively utilized due to losses, outdated

[1] Khoja Akhmet Yassawi International Kazakh-Turkish University, Faculty of Natural Sciences, Department of Ecology and Chemistry, Turkestan, Kazakhstan

infrastructure, and uneven regional distribution.

The Syr Darya, Ili, Irtysh, and Ural river basins face significant pressure as a result of intensive water withdrawal, industrial pollution, and reduced inflows caused by upstream use [2]. These challenges underline the urgent need for improved monitoring systems, modern irrigation practices, and strengthened international cooperation to ensure sustainable water management.

This paper aims to analyze the current state of Kazakhstan's water resources, explore trends in their utilization across major sectors, and review modern approaches to integrated and sustainable water management [3].

Water use in Kazakhstan varies considerably across economic sectors, reflecting both the structure of the national economy and regional climatic differences. Table 1 presents the sectoral distribution of water utilization, highlighting the dominant role of agriculture and the comparatively smaller shares of industrial and municipal consumption.

Table 1. Sectoral Distribution of Water Use in Kazakhstan

This table shows the main river basins of the country:

№	Sector	Share of Total Water Use (%)
1	Agriculture	65
2	Industry	20
3	Municipal and domestic use	12
4	Energy and cooling	3

2 Materials and Methods

The Syr Darya, Ili, Irtysh, and Ural river basins are among the most significant in Kazakhstan, providing water for irrigation, hydropower, and industrial purposes. However, they also face serious ecological and transboundary management challenges [4].

Table 2 presents the key hydrological parameters, dominant uses, and major environmental issues associated with each basin.

Spatial assessment was conducted using GIS-based mapping tools to identify regions most affected by water scarcity. Hydrological and climatic data were analyzed from sources such as the Kazhydromet Agency and satellite datasets [5].

A comparative analysis of water management frameworks was also carried out to evaluate the effectiveness of current policies, infrastructure modernization programs, and transboundary cooperation initiatives [6].

Table 2. Major River Basins of Kazakhstan

This table shows the main river basins of the country:

№	Annual Flow and Primary Uses
5.	**Syr Darya** — 37 km³/year, irrigation and hydropower
6.	**Ili** — 14.6 km³/year, agriculture and drinking water supply
7.	**Irtysh** — 33.8 km³/year, industry and energy
8.	**Ural** — 10 km³/year, agriculture and fisheries
9.	**Tobol–Ishim** — 5 km³/year, domestic use

3 Results

3.1. Current State of Water Resources

Kazakhstan's water sector continues to experience growing pressure due to climate change, population growth, and intensive agricultural activity. Despite government programs aimed at modernizing irrigation and improving water distribution, overall water efficiency remains low. According to the Ministry of Ecology and Natural Resources [1], nearly 60–65% of total water withdrawals are used in agriculture, with industry and domestic sectors accounting for smaller shares.

Significant progress has been made in expanding the area of irrigated lands through the implementation of water-saving technologies such as drip and sprinkler irrigation [7]. By 2024, the total area of irrigated land using modern technologies had reached approximately 462,200 hectares, representing a 48% increase compared to 2020 [8]. However, due to aging infrastructure and losses during transport, only about 42% of total renewable water resources are effectively available for consumption [9].

Another major concern is Kazakhstan's dependence on transboundary water inflows, which account for nearly 45% of its total renewable water supply [10]. This dependence on upstream countries such as China, Kyrgyzstan, and Uzbekistan underscore the importance of international agreements and integrated water resource management (IWRM) [11]. Table 3 summarizes recent key indicators that illustrate the current trends and challenges in Kazakhstan's water use and infrastructure development.

Table 3. Recent Key Indicators of Water Use and Infrastructure in Kazakhstan (2023–2025)

№	Indicator	Value	Year	Source
1	Share of water consumption used by agriculture	~60–65 %	2024	Astana Times (2024)
2	Area of irrigated land with modern water-saving technologies	~462,200 ha	2024	Astana Times (2024)
3	Percentage of renewable water resources formed outside Kazakhstan	~44–46 %	2023–24	PrimeMinister.kz
4	Percentage of total renewable water effectively available for consumption	~42 %	2025 (estimate)	Earth.org
5	Total renewable water resources (annual)	~100 km³	2024	Ministry of Ecology, Kazakhstan

As shown in Table 3, the dominance of agricultural water use remains a defining characteristic of Kazakhstan's water economy. The modernization of irrigation systems is progressing, yet the efficiency of water distribution networks remains a challenge.

The government's strategy emphasizes digital monitoring, satellite-based assessment, and regional cooperation as critical tools for achieving sustainable water management and climate resilience.

3.2. Water Use by Sector

Agriculture remains the largest water consumer, accounting for approximately 65–70% of total water withdrawals. However, irrigation efficiency remains low (around 40%) due to outdated canal systems and losses through evaporation. Industrial and energy sectors consume 20–25%, while domestic use represents about 10%.

Urbanization has increased demand in southern cities such as Shymkent, Taraz, and Almaty, putting additional pressure on local reservoirs.

3.3. Water Quality and Pollution

Industrial effluents, agricultural runoff, and mining activities contribute significantly to surface water pollution. Elevated levels of heavy metals, nitrates, and oil products have been detected in major river systems. According to national monitoring (Kazhydromet, 2023), about 30% of surface

4 Discussion

Sustainable management of water resources in Kazakhstan requires a careful balance between economic development, agricultural productivity, and environmental protection [12]. Over the past few years, the government has made tangible progress in implementing the principles of Integrated Water Resources Management (IWRM) [13], yet institutional fragmentation and limited financial resources continue to constrain its effectiveness. The newly established Ministry of Water Resources and Irrigation has become the central coordinating body, aiming to unify policies and reduce duplication of functions across different agencies.

Recent government initiatives have focused on modernization, digitalization, and technological efficiency [14]. Under the Digital Kazakhstan program, automated metering systems and remote sensing platforms have been introduced to monitor water distribution and consumption in real time [15]. In 2024, the government launched pilot projects using AI-based drought prediction models and satellite data to optimize irrigation scheduling in Almaty, Turkestan, and Kyzylorda regions.

These systems significantly reduce water losses and improve decision-making in agriculture.

In addition, Kazakhstan is actively expanding water-saving technologies such as drip and sprinkler irrigation, supported by state subsidies covering up to 85% of installation costs [16]. In 2024 alone, over 158,000 hectares were equipped with water-efficient systems, demonstrating a major step toward sustainable agricultural water use.

Transboundary water management remains a critical issue for regional security and ecological balance. Kazakhstan continues active negotiations with China on the joint management of the Ili and Irtysh rivers and with Uzbekistan and Kyrgyzstan within the Syr Darya basin framework. Despite some progress, cooperation is hindered by inconsistent data exchange, different national priorities, and limited joint monitoring infrastructure.

Strengthening institutional partnerships, adopting unified data standards, and establishing shared hydrological observatories would enhance transparency and trust among riparian states [17-19].

Overall, while the integration of smart technologies and international collaboration represents a positive shift, achieving long-term water sustainability in Kazakhstan will require stable funding, cross-sectoral coordination, and continuous scientific research.

5 Conclusion

Kazakhstan's water resources are under intensifying pressure from climate change, population growth, industrial expansion, and transboundary dependencies [20]. Although substantial progress has been made through digital transformation and legal reforms, water scarcity and uneven distribution remain persistent challenges [20].

The findings of this study suggest that future water management strategies in Kazakhstan should prioritize the following directions:

- Rehabilitation and modernization of irrigation infrastructure, with an emphasis on reducing losses and improving delivery efficiency;
- Wider adoption of water-saving and precision irrigation technologies to ensure sustainable agricultural productivity;
- Expansion of groundwater exploration and utilization in arid and semi-arid regions to diversify water sources;
- Development of an integrated hydrological monitoring and forecasting network, supported by digital tools and remote sensing;
- Strengthening transboundary water diplomacy through transparent data sharing and coordinated basin management;
- Integration of climate resilience, circular economy principles, and green technologies into all stages of water resource planning.

Sustainable management of Kazakhstan's water resources will depend on coordinated efforts among government institutions, scientific and technical communities, private sector stakeholders, and international partners. Achieving this synergy is essential to ensure long-term water security, food safety, and environmental stability across the country and the broader Central Asian region.

References

1. European Environment Agency (EEA). Air pollution sources and impacts. 2023.
2. World Health Organization (WHO). Ambient Air Pollution: A Global Assessment of Exposure and Burden of Disease. Geneva, 2022.
3. Chen Y. et al. Air Pollution from Oil Refining and its Health Effects. Environmental Research, 2023.
4. Kazemi, M., et al. Advanced Air Monitoring Technologies in Petroleum Industry. Journal of Environmental Engineering, 2024.
5. Li, X. et al. Chromatographic Analysis of Volatile Organic Compounds in Industrial Emissions. Atmospheric Chemistry and Physics, 2023.
6. NASA MODIS Satellite Data. Global Atmospheric Composition Monitoring. 2024.
7. US EPA. AERMOD User's Guide. 2023.
8. Al-Ghamdi, S. et al. Assessment of Air Quality Around Oil Refineries. Environmental Pollution, 2022.
9. Zhang, T. et al. Formation of Secondary Aerosols from NOx Emissions in Industrial Zones. Atmospheric Environment, 2023.
10. World Meteorological Organization (WMO). Global Sulfur Emissions Report. 2023.
11. IARC. Volatile Organic Compounds and Cancer Risk. 2022.
12. Luo, Q. et al. Catalytic Oxidation of VOCs: Recent Advances. Applied Catalysis B: Environmental, 2024.
13. OECD. Recovery and Recycling Technologies in Oil Refining. 2024.
14. Xu, L. et al. Green Catalysts in Petroleum Processing. Journal of Cleaner Production, 2023.
15. Wang, H. et al. AI-based Air Quality Prediction in Industrial Areas. Environmental Modelling & Software, 2024.
16. UNEP. Towards Carbon-Neutral Oil Refining. United Nations Environment Programme,

2024.
17. European Commission. Industrial Emissions and Air Quality Monitoring Strategies in the EU. Brussels, 2023.
18. Liu, J. et al. Artificial Intelligence Applications in Air Quality Monitoring. Environmental Science & Technology, 2024.
19. BP Energy Outlook. Decarbonizing the Refining Sector: Pathways and Technologies. 2024.
20. Ministry of Ecology and Natural Resources of the Republic of Kazakhstan. National Air Quality Strategy 2030. Astana, 2024.

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third-party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

SCIENCE, SUSTAINABILITY, AND TECHNOLOGY

The chapters collected in this book represent diverse yet interconnected fields, including environmental and plant sciences, public and environmental health, and the transformative role of modern technologies in education and medical training. While each chapter addresses a distinct research problem, all are united by a shared commitment to evidence-based analysis and practical application. Together, they demonstrate how interdisciplinary research can generate solutions that are both innovative and grounded in real-world needs.

9 786277 901158

WAH ACADEMIA PUBLISHING