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Analysis of laws to mitigate GHGS emission in developed countries

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Abstract

This study examines the evolution of greenhouse gas (GHG) mitigation laws in developed countries, focusing on legislative trends, policy frameworks, and their role in global climate governance. Using the Human Development Index (HDI) to classify developed nations, mitigation laws were systematically extracted from the Climate Change Laws of the World (CCLW) database. The study categorizes these laws into resource, actor, and governance systems within a socio-ecological framework, further subdivided into 19 key subsystems. Since 1976, 59 developed countries have enacted 367 mitigation laws, accounting for 62% of global mitigation legislation. While early laws were limited in scope, the enactment of international agreements such as the Kyoto Protocol (1997) and the Paris Agreement (2015) accelerated legislative efforts. The most substantial increase occurred after 2000, with Germany leading in legislative activity. Despite progress, challenges persist, including enforcement gaps, financial constraints, and conflicting economic priorities, which can hinder the effectiveness of these laws. A temporal and spatial analysis of mitigation laws indicates a shift from isolated policies to comprehensive strategies incorporating financial mechanisms, carbon pricing, and green economic initiatives. Europe leads in legislative efforts, followed by the Americas and Asia. The study also highlights the predominant focus on energy, transport, and building sectors, emphasizing the role of policy in driving low-carbon transitions. While these laws contribute to emission reduction, further research is needed to assess their real impact, policy coherence, and enforcement mechanisms. Strengthening implementation frameworks will be essential to achieving long-term climate goals.

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Introduction

Climate change legislation has become a crucial tool for addressing greenhouse gas (GHG) emissions. Developed countries have enacted a growing number of laws aimed at reducing emissions by transitioning to renewable energy, implementing carbon pricing mechanisms, and promoting low-carbon transportation (UNDP, 2020). These legislative frameworks support compliance with international commitments such as the Paris Agreement and establish structured approaches for emission reductions (Erbach, 2021). By 2020, 56 countries had implemented direct climate laws, collectively covering 53% of global emissions (Rumble & Gilder, 2022). Research on climate change legislation has explored its effectiveness in emission reduction. Iskandar and Fankhauser (2020) analyzed regulatory actions across 133 countries, concluding that climate laws contribute to a measurable decline in carbon dioxide emissions. Farzaneh and Banimostafaarab (2023a, 2023b, 2025) examined climate adaptation and disaster risk management laws, identifying an evolution toward broader policy objectives. Additional studies have assessed legislative trends in specific sectors, such as water, agriculture, and urban planning, reinforcing the predominance of mitigation laws in developed countries (Fakhri et al., 2023a, 2023b; Farzaneh et al., 2023; Banimostafaarab et al., 2023). However, gaps remain in understanding the structural axes and strategic priorities of mitigation laws, necessitating further research.

The urgency of mitigation stems from the need to curb GHG emissions and enhance carbon sequestration (Heshmati, 2021). The Intergovernmental Panel on Climate Change (IPCC) defines mitigation as a key strategy applicable across sectors, including energy, transportation, construction, industry, and land management (IPCC, 2023). Given their high energy consumption and historical emissions, developed nations play a critical role in these efforts, with countries like the United States, Germany, and Japan accounting for a significant share of cumulative emissions over the past 170 years (Papovich & Plumer, 2021).

While climate laws have driven emission reductions, their effectiveness varies based on governance structures, enforcement mechanisms, and political commitment. Many developed countries have integrated mitigation into broader national strategies, incorporating financial mechanisms and green initiatives (Farzaneh & Banimostafaarab, 2023a & 2023b). However, assessing the long-term impact of these laws requires a deeper examination of their legislative evolution and implementation.

This study fills existing research gaps by systematically analyzing mitigation laws in developed countries. Using the Climate Change Laws of the World (CCLW) database, it categorizes mitigation laws within a socio-ecological framework, focusing on three primary systems: resources, actors, and governance. The study further examines temporal and spatial trends, identifying key subsystems and their interconnections. By evaluating how these laws have evolved and their role in climate governance, this research provides insights into their effectiveness in achieving long-term emission reduction targets.

Materials and Methods

Review of development of countries

The United Nations Development Programme (UNDP) introduced the Human Development Index (HDI) in 1990 as part of the Human Development Report (Bagolin

& Comim, 2008). The HDI is a composite index that measures average achievements across three key dimensions of human development: a long and healthy life, education, and a decent standard of living (Conceição, 2022). The HDI value ranges from zero to one (UNDP, 2021). Developed countries typically exhibit high HDI values (0.8 or higher), classifying them within the "very high human development" category. These countries are characterized by stable governance, accessible education and healthcare systems, high life expectancy and quality of life, and robust economic growth (World Population Review, 2023). For this study, developed countries were identified based on their HDI values, as presented in Table 1.

The analysis focused on 59 developed countries, which were selected based on their HDI scores and included in the study due to their classification as "very high human development" nations. Countries that did not meet the HDI threshold for high development (below 0.8) were excluded from the analysis. This criterion ensures a consistent and comparable sample of nations with the capacity and infrastructure to implement and enforce climate change mitigation laws. It is important to note that while there is no direct relationship between a country's HDI value and the number of mitigation laws it has enacted, the inclusion of HDI serves solely to classify the countries as developed. There is no implied causality or correlation between HDI and legislative activity.

Table 1 presents the HDI values for each country along with the number of

Table 1. The HDI of developed countries and the number of mitigation laws related to climate change

Country	Human Development Index (HDI)	Number of mitigation laws	Country	Human Development Index (HDI)	Number of mitigation laws
Andorra	0.858	6	Luxembourg	0.930	6
Argentina	0.842	9	Malaysia	0.803	4
Australia	0.951	10	Malta	0.918	2
Austria	0.916	6	Mauritius	0.802	3
Bahamas	0.812	2	Montenegro	0.832	2
Barbados	0.810	2	Netherlands	0.941	6
Belarus	0.808	6	New Zealand	0.937	4
Belgium	0.937	8	Norway	0.961	9
Bulgaria	0.800	4	Oman	0.816	1
Canada	0.936	6	Palau	0.800	3
Costa Rica	0.809	5	Panama	0.805	7
Chile	0.855	7	Poland	0.876	12
Croatia	0.858	8	Portugal	0.866	2
Cyprus	0.896	1	Qatar	0.855	1
Czechia	0.889	6	Romania	0.821	10
Denmark	0.948	5	Russia	0.822	2
Finland	0.94	9	Serbia	0.802	3
France	0.903	9	Singapore	0.939	7
Georgia	0.802	3	Slovakia	0.848	10
Germany	0.942	20	Slovenia	0.918	2
Greece	0.887	15	South Korea	0.925	13
Hungary	0.846	4	Spain	0.905	9
Iceland	0.959	3	Sweden	0.947	4
Ireland	0.945	11	Switzerland	0.962	3
Israel	0.919	3	Turkey	0.838	5
Italy	0.895	14	UAE	0.911	2
Japan	0..925	13	UK	0.929	13
Kazakhstan	0.811	5	Uruguay	0.809	6
Kuwait	0.831	2	USA	0.921	9
Liechtenstein	0.935	5			

(UNDP,2021; Climate Change Laws of the World,2022) mitigation laws enacted. While this table highlights the number of laws per country, the scope and limitations of this research must be considered due to the variations in legislative approaches and the context in which these laws are enacted.

Quantitative Analysis: Time-Series Analysis of Climate Legislation

This study employs time-series analysis to examine trends in climate change mitigation legislation over time. The analysis focuses on identifying patterns in legislative activity, observing how the number and distribution of enacted laws have evolved across different periods. This approach allows for a structured evaluation of legislative developments in response to climate policies and international agreements.

Qualitative Analysis: Ostrom Framework

To systematically analyze climate change mitigation legislation, this study applies the Ostrom framework, a widely recognized socio-ecological system (SES) framework that provides an integrated approach to governance and policy interactions (Palomo & Hernández-Flores, 2019). The Ostrom framework consists of several first-order components, including social and ecological factors, external influences, system interactions, and outcomes, which are further divided into second-order variables (Nagel & Partelow, 2022). It defines the interactions between four key subsystems: resource units, resource systems, governance systems, and users (actors) (Ostrom, 2009). These subsystems operate within social, economic, and political environments, shaping policy effectiveness and legislative outcomes.
Given the international scope of this study and the absence of clear geographical boundaries, the analysis focuses on three primary systems: resources, actors, and governance. Each system comprises several subsystems, identified through thematic content analysis of GHG emission reduction laws (Del Mar Delgado-Serrano & Ramos, 2015; Climate Change Laws of the World, 2022):

- Resource System: Includes six subsystems that regulate environmental conditions where resources are located or produced: land use, land use change and forestry (LULUCF), coastal zones, cross-cutting areas, environment, waste, and water.
- Actor System: Encompasses seven subsystems representing stakeholders that influence or are affected by resource systems: energy, buildings, transport, industry, agriculture, health, and tourism.
- Governance System: Addresses decision-making processes in climate mitigation policies and comprises six subsystems: economy-wide, public sector, finance, rural, urban, and social development.

All mitigation laws were assigned to these three systems using predefined categories derived from the SES framework (Del Mar Delgado-Serrano & Ramos, 2015). Each law was classified based on its primary legislative focus, ensuring consistency in categorization.
Laws were analyzed within the Ostrom framework using textual analysis to extract legislative themes and identify policy priorities. The analysis focused on evaluating how mitigation laws align with governance structures, actors, and resource management strategies. However, no inter-coder reliability assessment was conducted in this study.

Data sources and limitations

The primary dataset was obtained from the Climate Change Laws of the World (CCLW) database, which provides an extensive collection of climate legislation. However, potential gaps in the CCLW database are acknowledged, as some laws may be missing due to differences in national reporting practices and data availability. To mitigate this limitation, supplementary data sources, such as national legislative repositories and government reports, were reviewed where possible. These gaps could influence the completeness of legislative trends observed in this study.

Results and discussion

Review of laws in mutual axes with mitigation

In developed countries, mitigation legislation extends beyond laws specifically targeting emissions reduction. Three additional axes are identified:

- mitigation and adaptation
- mitigation, adaptation, and disaster risk management
- mitigation and disaster risk management

Figure 1 illustrates the distribution of laws across these axes. The mitigation and adaptation axis exhibits the most extensive legal framework. Conversely, the number of laws pertaining to the other two axes is relatively small, likely due to their more recent emergence.

- Mitigation and Adaptation

The legislative framework for mitigation and adaptation in Belarus began in 1992 with the adoption of the Environmental Law. This area has seen significant legislative activity, with a total of 69 laws referencing the actor system. In terms of resource, actor, and governance systems, the sectors of LULUCF received the most attention, with 18 references. The transport sector followed with 25 references, while the economy-wide was mentioned in 24 laws. Among the countries studied, Georgia leads with the highest number of laws in this area, totaling five. The United Kingdom, New Zealand, France, and Denmark closely follow, each with four laws.

- Mitigation, adaptation and disaster risk management

Mitigation, adaptation, and disaster risk management axis has garnered attention in recent years, with its inaugural law being approved in 2019 as part of Turkey's 11th National Development Plan. Within this framework, the governance system is mentioned more frequently than other systems, with a total of 10 mentions. In terms of resources, actors, and governance, the economy-wide stands out with 4 mentions, followed by the water sector with 3 mentions, and economy-wide, which received 2 mentions. Notably, Turkey, Mauritius, the United States, Portugal, and Chile each have enacted one law pertaining to this axis.

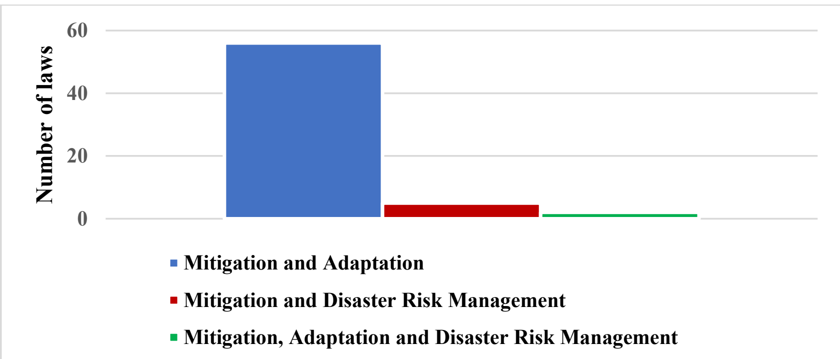

Fig 1. The number of laws in the mutual axes of climate change mitigation.

• Mitigation, adaptation and disaster risk management

This area has recently become a major focus for new regulations. To date, only two legislative enactments have been observed within this axis: the U.S. Consolidated Appropriations Act of 2020 and the U.K. Subsidy Control Act of 2022.

Within this axis, the governance system exhibits a higher frequency of mention (three mentions) compared to the actor system (one mention). Notably, no legislative provisions were identified specifically addressing the resource system. The subsystems most frequently mentioned within this axis include the economy-wide (two mentions), energy, and finance (each with one mention).

Time and spatial review of climate change mitigation laws

As of 2022, the CCLW database recorded 928 enacted climate change-related laws worldwide. Developed countries accounted for a significant portion of this legislation, enacting 499 laws, representing 54% of the global total.

Focusing on subject matter, 593 laws (64% of all climate change legislation) specifically addressed mitigation. Of these, 367 originated from developed countries, constituting 62% of all mitigation laws globally. This further translates to 40% of all climate change-related laws enacted worldwide.

Figure 2 illustrates time review of mitigation laws enacted in developed countries. The first such law, the Norwegian Product Control Act No. 79, was enacted in 1976. However, legislative activity in this domain remained relatively slow, with only five additional laws enacted by 1988. From 1988 onwards, legislative activity accelerated, with at least one law enacted annually. By the year 2000, a total of 45 mitigation laws had been enacted, constituting 12% of all such laws. This indicates that the majority of mitigation laws in developed countries have been enacted since the year 2000.

A period of heightened legislative activity occurred between 2008 and 2015, with at least 18 laws enacted annually. This surge can be attributed to the commitments made by member states of the Kyoto Protocol to reduce GHG emissions.

Despite this progress, the urgency of addressing GHG emissions remains evident, as demonstrated by the enactment of five new laws in 2022 alone in countries such as France, Germany, Italy, and Spain.

A spatial review of climate change

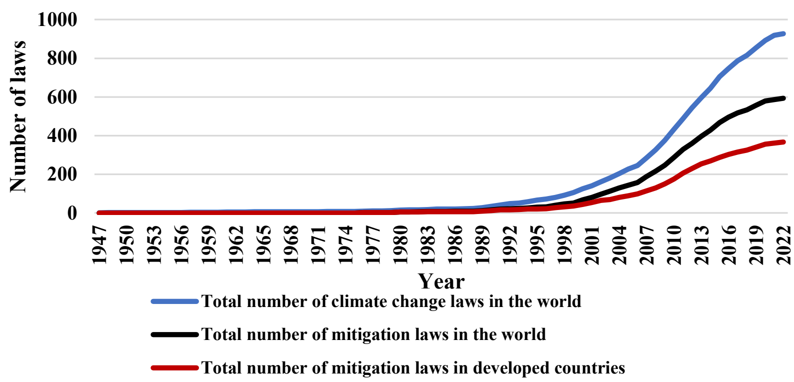

Fig 2. Time review of climate change mitigation laws.

mitigation laws reveals a significant disparity across continents. Of the 59 developed countries included in this study, 37 are located in Europe, 9 in the Americas, 9 in Asia, 3 in Oceania, and 1 in Africa (Figure 3).

Europe demonstrates the highest concentration of mitigation legislation, with 246 enacted laws, constituting 67% of the global total. The Americas follow with 53 laws (14%), Asia with 48 laws (13%), Oceania with 17 laws (5%), and Africa with 3 laws (1%).

Within Europe, Germany, Greece, and Italy stand out as leaders in mitigation legislation, having enacted 20, 15, and 14 laws, respectively. In the Americas, the United States leads with 9 enacted laws. In Asia, both South Korea and Japan are leading in this domain, each with 13 enacted laws.

Time and spatial review of climate change mitigation laws in in Socio-Ecological Systems

This section analyzes how legal frameworks for GHG emission reduction address each component of the socio-ecological system. As Figure 4 demonstrates, the actor system receives the most attention, with a substantial 565 mentions. The resource system follows with 93 mentions, while the governance system has the fewest, with 48.

Mentions across all three systems emerged in 1976, starting with the German Energy Saving Act within the actor system and the Norwegian Product Control Act No. 79 in both the resource and governance systems. Since 2000, the frequency of mentions across all systems has markedly increased. In the actor system, this upward trend

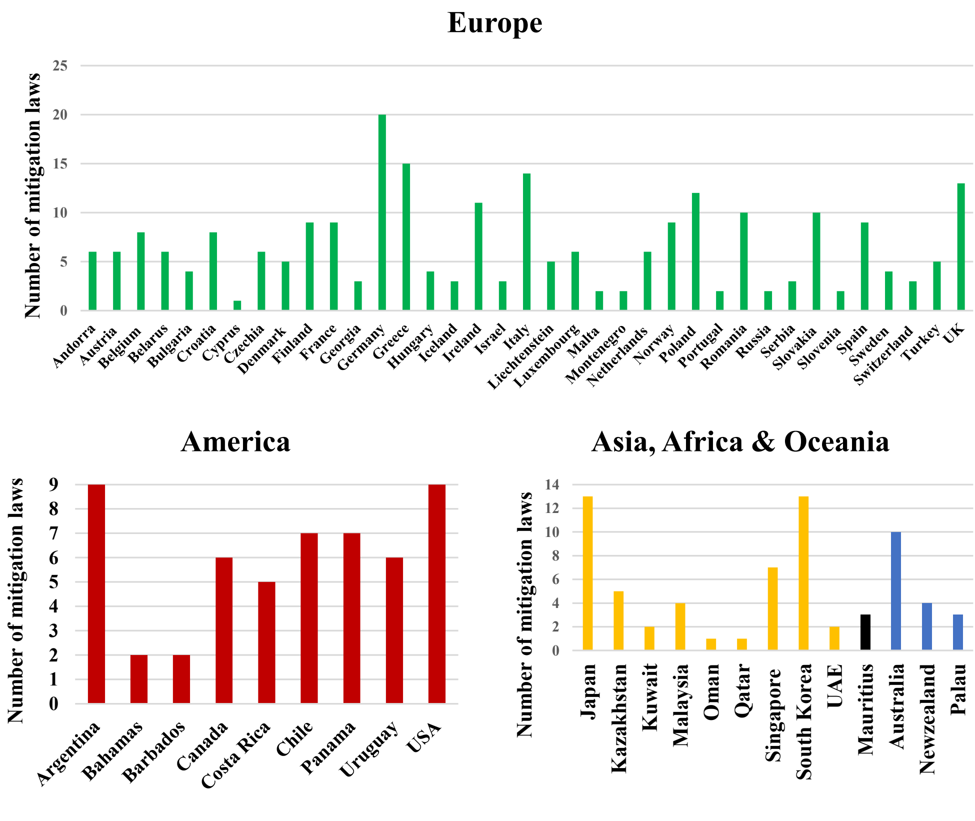

Fig 3. Spatial review of climate change mitigation laws.

peaked between 2007 and 2016, with at least 26 mentions annually. The resource system experienced its most significant increase between 2006 and 2012, with a minimum of six annual mentions. Since 2014, the governance system has also seen growing emphasis, with at least two annual legislative mentions. Figure 4 presents a time series visualizing the frequency of legal mentions to each system within mitigation legislation.

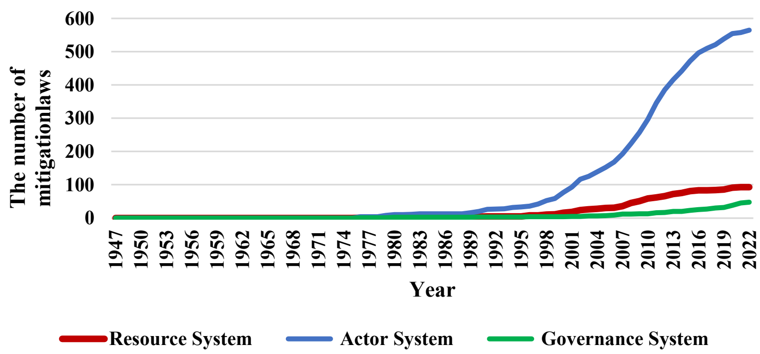

Fig 4. Time review of the climate change mitigation laws in socio-ecological systems.

The spatial review of socio-ecological systems by continent, as depicted in Figure 5, reveals that Europe exhibits a higher share of legislative mentions across all three systems: resources, actors, and governance. Specifically, Europe accounts for 62 mentions in the resource system, 328 in the actor system, and 28 in the governance system. Notably, the actor system consistently ranks highest across all continents, followed by the resource and governance systems, except in Africa. In Europe, 26 countries have enacted legislation related to the resource system, with Belarus and Italy leading with six mentions each. In the actor system, all countries have enacted relevant legislation, with Germany and Italy again demonstrating the highest activity, each with 30 mentions. However, in the governance system, only 16 countries have enacted legislation, with France leading with seven mentions. The majority of countries in this system have only one or two mentions, suggesting a relatively low emphasis on governance in mitigation legislation.

In the Americas, seven countries have legislation related to the resource system, with Canada leading with five mentions. In the actor system, all countries have at least two mentions, with the United States demonstrating the highest share with 22 mentions. The governance system is addressed by only five countries, with Canada again leading with three mentions. In Asia, six countries have legislation related to the resource system, with South Korea leading with three mentions. In the actor system, all countries except Oman have enacted relevant legislation, with Japan demonstrating the highest share with 26 mentions. In the governance system, only four countries have enacted legislation, with Japan again leading with nine references. It is important to note that while Oman has mitigation laws, it does not fall within the scope of the socio-ecological systems framework in this analysis. In Oceania, Australia demonstrates the highest shares in the resource and actor systems, with three and 13 mentions, respectively. However, no legislation has been approved for the governance system in Oceania. In Africa, only the actor system is recognized, with no legislation established for the resource or governance systems.

Time and spatial review of climate change mitigation laws in in the Resource System

The resource system, based on the frequency of mitigation laws in developed countries, consistently encompasses the subsystems of "waste" (31 laws), "water" (26 laws), "LULUCF" (23 laws), "environment" (10 laws), and "cross-cutting areas" (3 laws). As depicted in Figure 6, the enactment of waste sector legislation commenced in 1976 with the Norwegian Product Control Act No. 79. Similarly, the water and LULUCF sectors were first addressed in the Singapore Building Control Act (1989) and the Costa Rican Energy Act (1990), respectively. Legislation within the environment sector began its trajectory in 1996 with the Costa Rica's Forest Act. Notably, a significant proportion of laws across all these subsystems have been enacted since 2007. While the number of laws remains relatively small, cross-cutting areas have emerged as a focal point for legislative attention in recent years. The inaugural law in this category, "Fuel Emission Trading," was enacted in Germany in 2019.

A spatial analysis of the resource system subsystems, as depicted in Figure 7, reveals varying legislative priorities across continents. In Europe, the waste sector

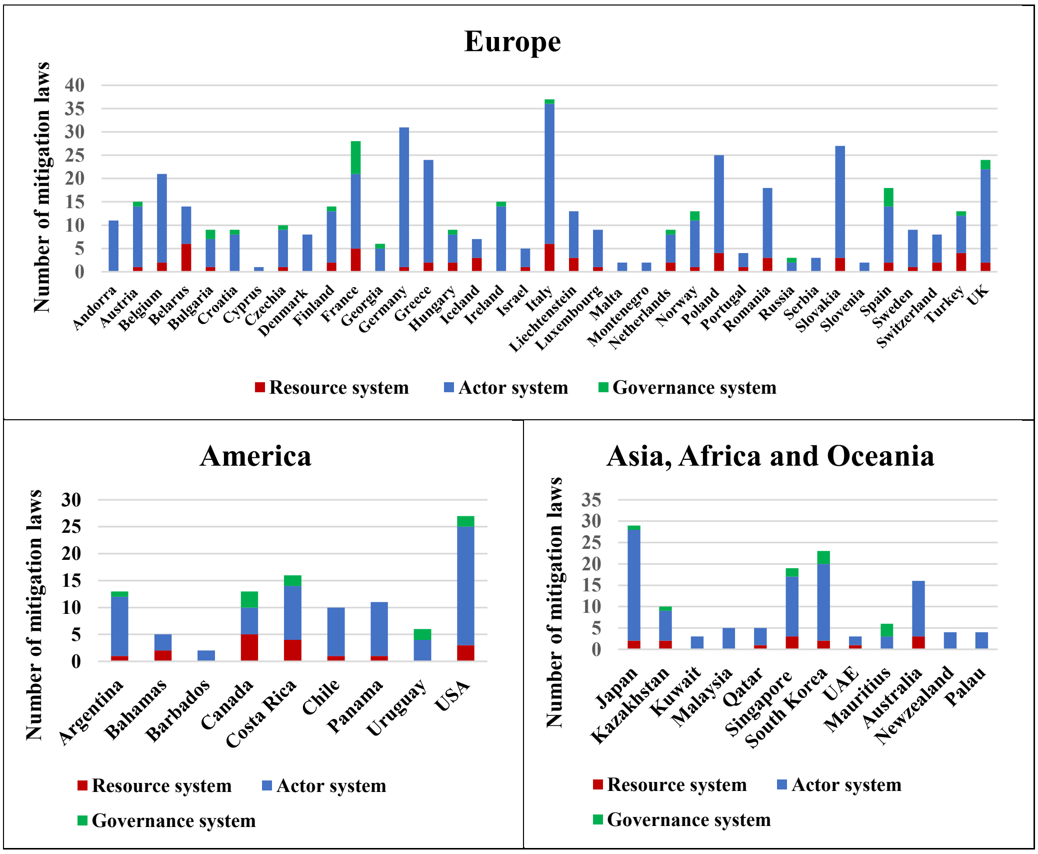

Fig 5. Spatial review of the climate change mitigation laws in socio-ecological systems

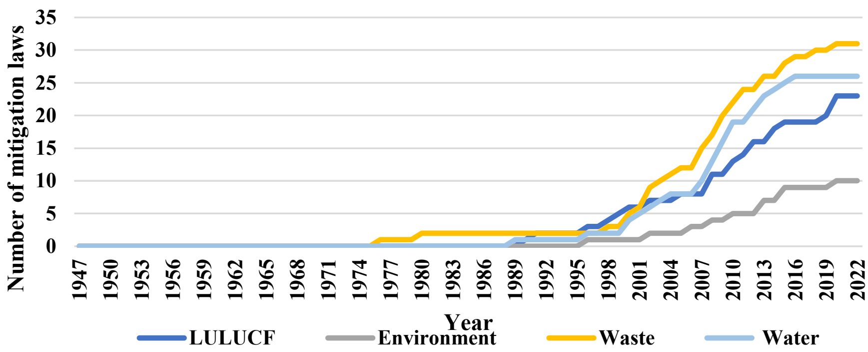

Fig 6. Time review of the climate change mitigation laws in the resource system

garners the highest number of mentions (22), followed by LULUCF (16), water (15), the environment (7), and cross cutting areas (2). Belgium and Italy lead with three mentions each, while Liechtenstein, Slovakia, and Switzerland contribute two mentions each. Notably, within the environment and cross cutting areas sectors, each European country contributes a maximum of one mention.

In the Americas, LULUCF sector holds the top position with six mentions. The water and waste sectors follow closely, each with four mentions, while the environment sector has two mentions, and cross cutting areas have one. Costa Rica and Barbados each contribute two mentions, alongside the United States. Similar to Europe, within the environment and cross cutting areas sectors, each country in the Americas has a maximum of one mention.

In Asia, the highest number of mentions are allocated to the water (5 mentions), waste (4 mentions), and environment and LULUCF sectors (one mention each). No laws are defined for cross cutting areas. Singapore leads with two mentions, while Japan, Kazakhstan, and Qatar each contribute one. In Oceania, only two mentions are found in the water sector and one in the waste sector, all attributed to Australia. Notably, no laws are defined for resource systems in the African continent.

Time and spatial review of climate change mitigation laws in in the actor system

The actor system, categorized by the frequency of mitigation laws in developed countries, comprises several subsystems: “Energy (275),” “Transport (145),” “Building (78),” “Industry (44),” “Agriculture (14),” “Health (8),” and “Tourism (1).” As illustrated in Figure 8, a substantial majority of these sector-specific laws have been enacted since 2000, with over half approved since 2010.

Legislative activity within the energy and building sectors commenced in 1976 with the German Energy Saving Act. The health sector saw its first regulatory measures in the same year with the Norwegian Product Control Act. The transport and industry sectors followed in 1979 with the Japanese Rational Use of Energy Act. The agricultural sector’s legislative journey began in 1991 with the Carbon Tax Act and related regulations. Finally, the tourism sector saw its first regulatory measure in 1996 with the Costa Rica’s Forest Act.

Spatial analysis of the subsystems mentioned in the regulations of the actor system, as depicted in Figure 9, reveals a continental distribution. In Europe, the energy sector dominates with 182

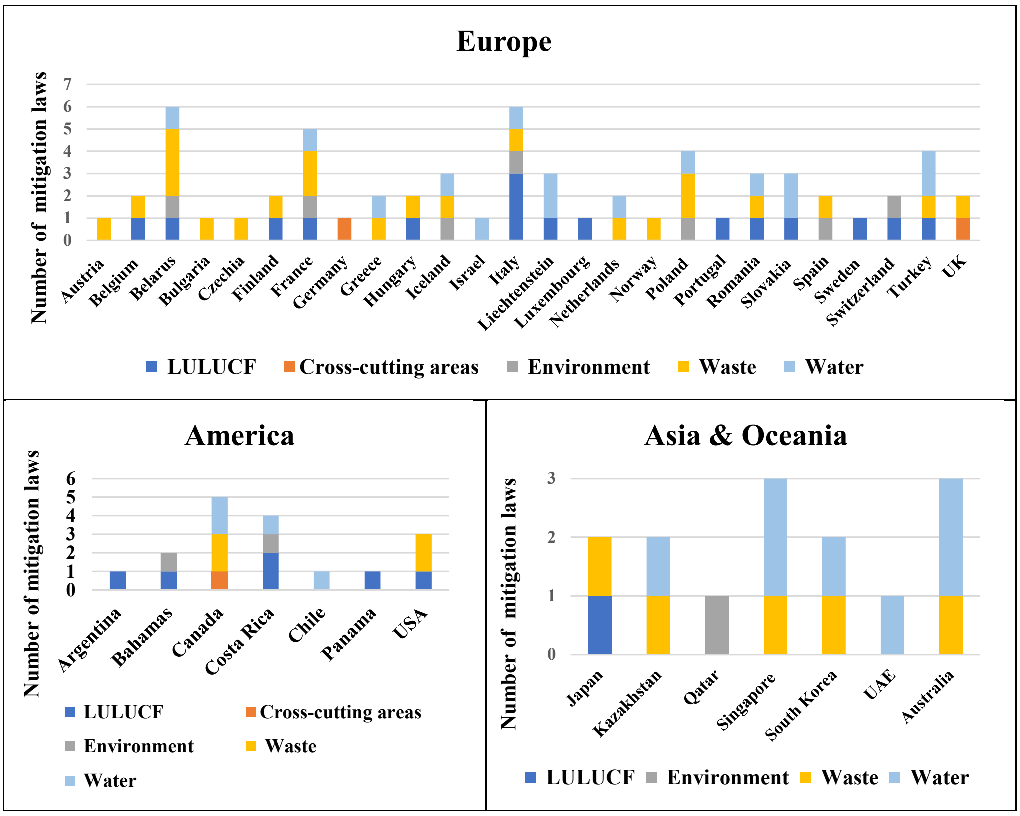

Fig 7. Spatial review of the climate change mitigation laws in the resource system

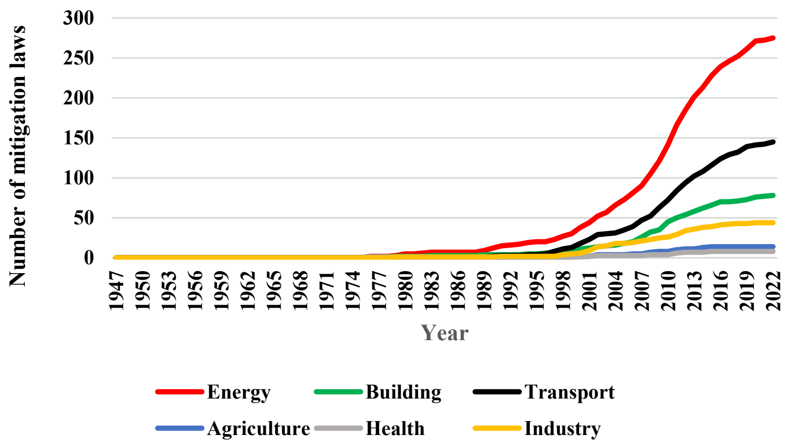

Fig 8. Time review of the climate change mitigation laws in the actor system.

mentions, followed by transport (108), building (55), industry (29), agriculture (9), and health (3).

Germany leads with 15 mentions across sectors, followed by Italy and the UK (8 each), Germany and Italy (6 each), Slovakia, Germany, and Belgium (3 each), and Poland (3). Within the health sector, each European country exhibits a maximum of one regulatory mention.

In America, all subsystems are mentioned, with energy holding the highest count (38), transport (17), building (11), industry (4), health (3), agriculture (2), and tourism (1) follow. The USA leads in energy (9), transport (6), and building (3), while the USA and Argentina share the lead in industry (2 each).

Asia demonstrates a strong focus on energy (39), transport (17), industry (11), building (9), agriculture (2), and health (1). Japan dominates in energy (12), transport (7), and building (4), while Singapore leads in industry (4). Other sectors in Asia exhibit a maximum of one mention per country.

In Oceania, energy (14), building (4), transport (2), agriculture, and health (each with 1) are the most mentioned subsystems. Australia leads across these sectors with 7, 3, 1, 1, and 1 mentions, respectively. Finally, in Africa, only the energy (2) and transport (1) sectors are addressed, both in Mauritius.

Time and spatial review of climate change mitigation laws in in the governance system

The governance system for mitigation laws in developed countries, informed by the frequency ranking comprises several key subsystems. These include the "economy-wide" (32 mentions), "urban" (7 mentions), "public sector" (3 mentions), "finance" (3 mentions), "social development" (2 mentions), and "rural" (1 mention).

As illustrated in Figure 10, this governance system has undergone regulatory evolution since the Product Control Act No. 79 in Norway (1976), which targeted the urban sector. However, regulatory attention within this system has been

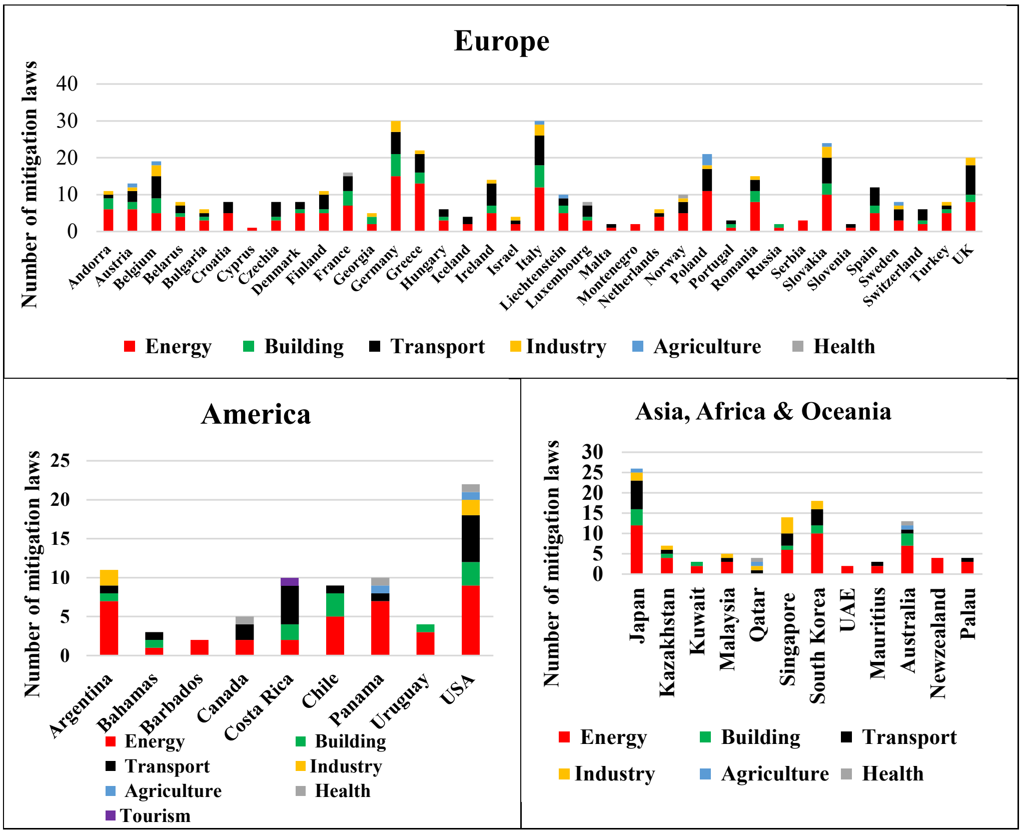

Fig 9. Spatial review of the climate change mitigation laws in the actor system.

relatively limited, with most subsystems experiencing significant regulatory activity only since 2006.

The "economy wide", initiated by South Korea's Energy Consumption Rationalization Act (1980), has seen a surge in regulations since 2015. The "social development" sector, exemplified by Law 26.093 (2006) Regimen of Regulation and Promotion of the Production and Sustainable Use of Biofuels (2006), has been a focus for regulatory action. The "rural sector" gained attention in 2011 with the Law on Act on the Creation and Facilitation of Use of Smart Grids. The "public sector" witnessed significant regulatory developments from 2017 onwards, including notable legislation in France and the UK (2020).

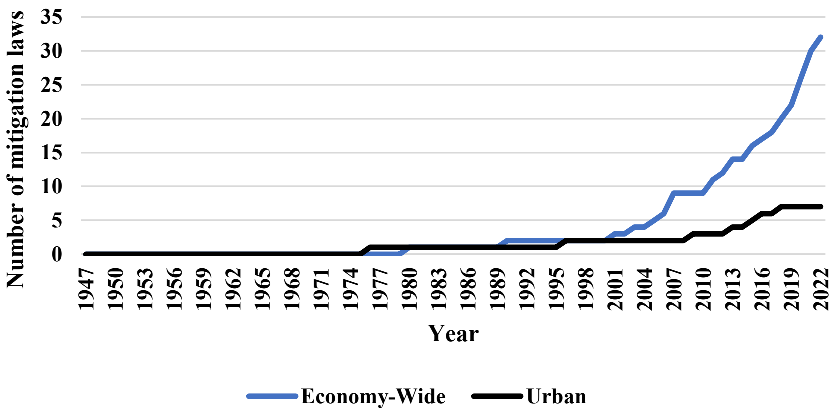

Fig 10. Time review of the climate change mitigation laws in the governance system.

Spatial analysis of the subsystems mentioned in governance system laws, as depicted in Figure 11, reveals that, with the exception of Oceania (which lacks such laws), the "economy wide" subsystem is most frequently mentioned across all continents. In Europe, the "economy wide" dominates with 19 mentions, followed by "urban" (4), "finance" (2), "public sector" (2), and "social development" (1). Spain (3), France (2), and the United Kingdom (2) are the primary sources of mentions across these sectors. Other sectors exhibit a maximum of one mention per country. In the Americas, "economy-wide" leads again with 7 mentions, followed by "urban" (2) and "social development" (1). Canada contributes 3 mentions, while Costa Rica contributes 2 to the "economy wide" and Argentina provides 1 mention each to "economy wide" and "urban." Asia demonstrates a focus on the "economy wide" (5 mentions), with additional mentions in the "rural" (1) and "urban" (1). Canada contributes 3 mentions, followed by Costa Rica with 2. Singapore is notable for having 2 mentions in the "economy wide". Finally, in Africa, Mauritius is the sole source of mentions, citing the "economy wide", "public sector", and "finance" once each.

Analysis of historical trends in mitigation laws within developed countries reveals a consistent upward trajectory in their adoption. Each decade has witnessed not only an increase in the number of such laws but also an expansion of their objectives and scope.

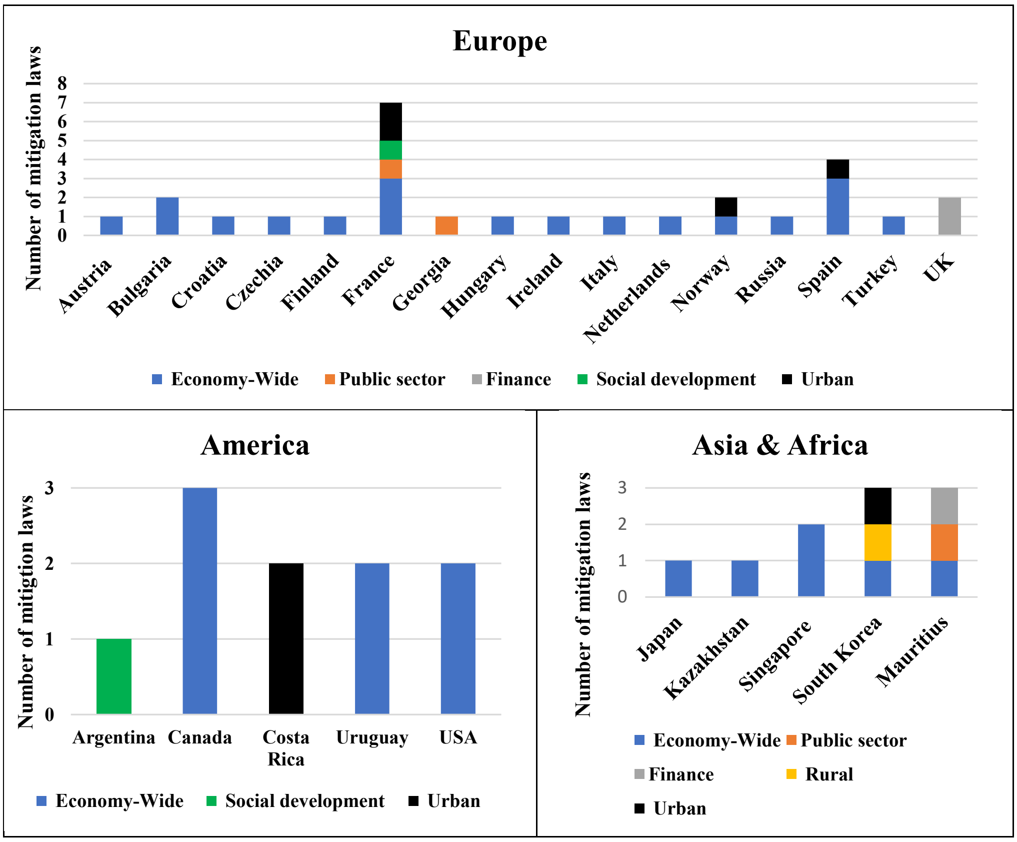

Fig 11. Spatial review of the climate change mitigation laws in the governance system.

The approval of mitigation laws commenced in the mid-1970s. During this era, characterized by limited awareness of climate change and its significance, efforts primarily focused on energy issues. Key examples include energy conservation initiatives in Germany, the promotion of energy-efficient products in Norway, and the advocacy for rational energy use, considered fundamental principles.

The 1980s witnessed a doubling of laws compared to the 1970s, with a notable surge in legislation within Asian countries. While energy-related concerns remained prominent, the objectives of these laws expanded to encompass national standards, regulations, policies, and programs. This period saw the establishment of energy efficiency standards in Japan, the formulation of a comprehensive GHG emission reduction policy in South Korea, the creation of the Atomic Energy Organization in Turkey, the implementation of Energy Conservation Performance Regulations in Kuwait, and the establishment of safety standards for buildings in Singapore.

The 1990s witnessed the enactment of 27 new laws aimed at mitigation, encompassing the establishment of policies, funds, and schemes. Key policy areas included the introduction of carbon taxes in Norway and Sweden, the creation of renewable energy and energy efficiency funds in Argentina and Belarus, the implementation of an environmental protection plan in Austria, the development of a comprehensive plan for integrated energy supply in South Korea, and the regulation of the electricity market in the Netherlands, Belgium, and Belarus, alongside the establishment of a GHG emission management system in Belarus. The 2000s saw a significant increase in mitigation legislation, with approximately one-third of all such laws enacted during this decade, signifying a growing awareness of this critical issue. This period witnessed the formulation of various strategic plans and national strategies, alongside the negotiation of climate change agreements. Key policy focuses included the establishment of national agencies, the implementation of tax regimes, and the development of nuclear energy programs. Notably, several laws explicitly referenced "mitigation" in their titles, including the establishment of the mitigation fund in Italy, the implementation of Norwegian Global Emission Reduction Initiative, the creation of Canada Emission Reduction Incentives Agency, and the establishment of the Greenhouse Gas Emissions Management System in Poland.

The signing of the Copenhagen Accord in 2009 spurred a significant increase in mitigation legislation during the 2010s, with over half of all such laws enacted within this decade.

In addition to the policy areas emphasized in the 2000s, this period witnessed the emergence of various "green" measures, including carbon and GHG pricing, and disclosure legislation. Notable examples include energy disclosure laws in Australia, green finance regulations in Portugal, energy transition policies for green growth in France, the promotion of green economy measures in Italy, initiatives for a green economy transition in Kazakhstan, the establishment of the Green Fund in Greece, and the implementation of carbon pricing in Singapore and Canada.

From 2020 to 2022, an additional 26 laws aimed at mitigation were enacted. The emergence of the COVID-19 pandemic during this period shifted the focus towards financial and economic recovery, leading to the introduction of legislation such as the French Anti-Waste and Circular Economy and Purchasing Power Parity Act, budget laws in the UK, and financial regulations in the UK, Ireland, France, and Mauritius. Looking ahead, the commitments made by member states of the United Nations Framework Convention on Climate Change (2020), particularly those of developed countries with historical responsibilities for GHG emissions, will likely drive further legislative efforts to reduce emissions. These laws, once enacted, have the potential to significantly impact GHG emission levels. While some may be implemented immediately, others may be rolled out gradually, with varying timelines. The effectiveness of these laws is contingent upon the strength of implementing regulations within each country, with a strong rule of law generally correlating with greater impact. Overall, it can be concluded that global mitigation laws have, on average, demonstrated effectiveness in lowering emissions.

Beyond examining international legal frameworks addressing climate change and natural disasters, it is essential to consider the key factors that influence their practical effectiveness. Elements such as political commitment to implementing international obligations, public support for climate policies and civil society engagement, as well as economic barriers that may hinder investments in adaptation and mitigation measures, play a decisive role in shaping the efficacy of global legal regimes. A critical analysis of these variables can provide deeper insights into the challenges surrounding compliance and enforcement, while also offering pathways to enhance institutional and state-level adherence to existing regulations.

Conclusion

This research provides a comprehensive analysis of climate change mitigation laws in developed countries, in the enactment of climate change mitigation laws since 1976. The analysis demonstrates a clear temporal evolution, with a surge in legislative activity following the Kyoto Protocol in 1997 and the Copenhagen Accord in 2009. Europe emerges as the leading region in terms of both the number of laws and the breadth of their scope. with countries such as Germany, the UK, and France enacting the highest number of mitigation laws and implementing extensive frameworks across various sectors, including energy, transport, and industry. The study identifies three key systems within the socio-ecological framework: resources, actors, and governance. The socio-ecological framework is an analytical tool that examines the interactions between social systems (e.g., actors and governance structures) and ecological systems (e.g., natural resources and environmental processes). In this context, the "actor" system, particularly the "energy," "transport," and "building" sectors, receives the most legislative attention, reflecting their significant contributions to GHG emissions. Notably, the "resource" system, specifically "waste" and "water" management, also demonstrates considerable legislative focus. Building on these findings, the analysis further reveals a shift from isolated legislative measures toward more comprehensive national programs, funding mechanisms, and sector-wide integration of climate policies. This evolution reflects a growing recognition that fragmented approaches are insufficient for meaningful GHG reductions. However, while legislative frameworks have expanded, the presence of laws alone does not guarantee their effectiveness. The strength of enforcement mechanisms, resource allocation, and political commitment significantly influence real-world outcomes. A key challenge remains the enforcement gap. Many countries with ambitious climate laws struggle with institutional capacity, financial constraints, and resistance from industries and political stakeholders. For instance, carbon pricing laws exist in multiple jurisdictions, yet weak compliance mechanisms and economic trade-offs often dilute their impact. Without stringent monitoring, reporting, and accountability structures, the intended benefits of mitigation policies may not fully materialize. To enhance the effectiveness of climate mitigation laws, policymakers should consider:

1. Strengthening Enforcement Mechanisms – Implement robust monitoring, reporting, and verification (MRV) systems, along with clear penalties for non-compliance.
2. Integrating Climate Policies Across Sectors – Align mitigation laws with energy, industrial, and economic policies to ensure consistency and avoid regulatory fragmentation.
3. Ensuring Political and Financial Commitment – Secure long-term funding and political stability to sustain implementation efforts. International cooperation can help bridge enforcement gaps, especially in regions with weaker institutional capacity.
4. Regular Policy Evaluation – Establish periodic assessments to measure legislative effectiveness, track emission trends, and incorporate technological advancements into legal frameworks.

Future research should move beyond legislative counts and focus on evaluating policy impact using quantifiable indicators such as emissions reduction rates, enforcement strength, and socio-economic feasibility. Additionally, examining the interaction between governance structures and legal outcomes will provide deeper insights into how laws translate into real-world climate action. Addressing these challenges will be crucial in ensuring that climate mitigation laws achieve measurable and lasting environmental benefits.

References

Bagolin, I., & Comim, F. (2008). Human Development Index (HDI) and its family of indexes: An evolving critical review. *Revista de Economia*, 34(2), 7–28. http://dx.doi.org/10.5380/re.v34i2.12293

Banimostafaarab, F., Banimostafaarab, E., & Farzaneh, M. R. (2023). *The approach of developed countries in climate change legislations in urban and rural sectors.* In The 2nd National and 1st International Conference on Modeling and New Technologies in Water Management, Birjand. [In Persian]

Climate Change Laws of the World. (2022). *Global Database of Climate Change Laws, Policies, and Targets.* Retrieved from https://climate-laws.org

Conceição, P. (2022). *Human development report 2021–22: Uncertain times, unsettled lives: Shaping our future in a transforming world.* https://hdr.undp.org/content/human-development-report-2021-22

Del Mar Delgado-Serrano, M., & Ramos, P. (2015). Making Ostrom's framework applicable to characterize social-ecological systems at the local level. *International Journal of the Commons, 9.* https://doi.org/10.18352/ijc.567

Erbach, G. (2021). *European climate law.* European Parliament.

Fakhri, M., Farzaneh, M. R., & Banimostafaarab, F. (2023a). *The roadmap for the water sector of developed countries in the face of climate change.* In The 2nd National and 1st International Conference on Modeling and New Technologies in Water Management, Birjand. [In Persian].

Fakhri, M., Farzaneh, M. R., & Banimostafaarab, F. (2023b). *The roadmap for the agriculture sector of developed countries in the face of climate change.* In The 2nd National and 1st International Conference on Modeling and New Technologies in Water Management, Birjand. [In Persian].

Farzaneh, M. R., & Banimostafaarab, F. (2023a). Analysis of climate change adaptation laws in developed countries (Persian). *Journal of Drought and Climate Change Research, 1*(1), 49–70. https://doi.org/10.22077/jdcr.2023.6024.1009

Farzaneh, M. R., & Banimostafaarab, F. (2023b). Analysis of climate change adaptation laws in developing countries (Persian). *Climate Change Research, 4*(13), 35–54. https://doi.org/10.30488/ccr.2023.394431.1128

Farzaneh, M. R., & Banimostafaarab, F. (2025). Climate change and DRM laws analysis in developed countries based on the SES framework. *Health in Emergencies and Disasters Quarterly, 10*(2), 95–106. http://dx.doi.org/10.32598/hdq.10.2.610.1.

Farzaneh, M. R., Banimostafaarab, F., Azizi, S. E., & Khaman, A. (2023). *Roadmap for environmental regulation of developed countries in the face of climate change.* In The 2nd National and 1st International Conference on Modeling and New Technologies in Water Management, Birjand. [In Persian].

Heshmati, E. M. (2021). Impact of climate change on life. *Environmental issues and sustainable development*, 1–20. https://doi.org/10.5772/intechopen.94538

IPCC. (2023). *Working group III mitigation of climate change.* Retrieved from https://www.ipcc.ch/working-group/wg3/

Nagel, B., & Partelow, S. (2022). A

methodological guide for applying the social-ecological system (SES) framework: A review of quantitative approaches. *Ecology and Society, 27*(4), 39. https://doi.org/10.5751/ES-13493-270439.

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science*. https://doi.org/10.1126/science.1172133

Palomo, L. E., & Hernández-Flores, A. (2019). Application of the Ostrom framework in the analysis of a social-ecological system with multiple resources in a marine protected area. *PeerJ, 7*, e7374. https://doi.org/10.7717/peerj.7374.

Papovich, N., & Plumer, B. (2021). Who has the most historical responsibility for climate change? *The New York Times*. Retrieved from https://www.nytimes.com/interactive/2021/11/12/climate/cop26-emissions-compensation.html

Rumble, O., & Gilder, A. (2022). *Climate change regulation 2022*. Chamber Global Practice Guides.

UNDP. (2021). Retrieved from United Nations Development Programme: http://hdr.undp.org

United Nations & Framework Convention on Climate Change. (2020). *Compilation and synthesis of fourth biennial reports of parties included in Annex I to the Convention*. United Nations and Framework Convention on Climate Change.

World Population Review. (2023). Human Development Index (HDI) by country 2023. Retrieved from https://worldpopulationreview.com/country-rankings/hdi-by-country

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Eco-friendly synthesis of magnetic $NiFe_2O_4$-chitosan nanocomposite for cyanide removal: a sustainable strategy for water resource management

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Climate change, Water resource management, Green Magnetic $NiFe_2O_4$, Chitosan, Cyanide removal

Abstract
The growing issue of water scarcity, exacerbated by climate change and extended droughts, underscores the critical need for effective water and wastewater treatment strategies. In this study, $NiFe_2O_4$ magnetic nanoparticles were synthesized using a green synthesis approach in peppermint (Mentha) extract medium, ensuring an eco-friendly fabrication process. The magnetic nanoparticles were coated and modified with chitosan, resulting in a new nanocomposite with improved adsorption properties. This green-synthesized magnetic chitosan nanocomposite was characterized using FTIR, XRD, VSM, SEM, and TEM, and subsequently applied to remove cyanide from contaminated groundwater and industrial wastewater. The adsorption process was optimized through an experimental design procedure, achieving a maximum removal efficiency of 97.1 ± 3.8% at a 95% confidence level, closely matching the experimental results of 95.8 ± 7.7%. The results highlight the potential of this sustainable nanocomposite for water and wastewater treatment, aiding effective water resource management in the face of climate change and growing water scarcity.

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Introduction

Various industries, especially mining, pharmaceuticals, and agriculture, use cyanide (CN-) compounds (Kuyucak & Akcil, 2013). As an essential ingredient in mining, cyanide facilitates the dissolution of Au and Ag silver through complexation reactions (reactions 1 and 2).

$$2Ag + 4CN^{-} + 1/2\ O_2 + H_2O \rightleftharpoons 2[Ag(CN)_2]^{-1} + 2OH^{-} \quad (1)$$

$$2Au + 4CN^{-} + 1/2\ O_2 + H_2O \rightleftharpoons 2[Au(CN)_2]^{-1} + 2OH^{-} \quad (2)$$

However, despite its industrial significance, cyanide is highly toxic, posing serious environmental and health hazards which can cause severe health complications even at concentrations as low as 0.2 $mg.L^{-1}$ (Dash et al., 2009a). Small amounts of cyanide can deactivate cytochrome oxidase, which ultimately prevents the so-called cellular respiration, which ultimately causes tremors, nerve damage, and eventually death (Beasley & Glass, 1998; Gracia & Shepherd, 2004; Hendry-Hofer et al., 2019). Due to this, they are commonly found in wastewater generated by these industries, posing significant environmental risks (Moussavi & Khosravi, 2010; Singh & Balomajumder, 2016). Given these risks and the extensive industrial use of cyanide, large quantities of cyanide-laden wastewater are continuously released into the environment, necessitating efficient and sustainable treatment methods.

Usually, cyanide-containing wastewater is treated by alkaline chlorination, which uses chlorine to convert cyanide into cyanogen chloride and sodium cyanate as intermediates, eventually converting them into non-toxic end products, i.e. CO_2 and N_2 (Dash et al., 2009a). This method effectively lowers cyanide levels; however, it creates toxic sludge and incurs high operational costs. Furthermore, chlorinated by-products may form when this sludge reacts with organic compounds in wastewater. Due to these limitations, there is a crucial need for alternative cyanide remediation strategies that are both cost-effective and environmentally sustainable.

Electrochemical techniques (Hassani et al., 2011; Scarazzato et al., 2015), ozone treatment (Chang et al., 2008), wet-air oxidation (WAO), and "acidification/volatilization/re-neutralization" (AVR) have also been utilized as CN- remediation alternatives. Electrochemical and WAO techniques are limited to small-scale operations (Pulkka et al., 2014), while ozonation equipment is prohibitively expensive. The use of biological methods is severely limited by the microbial and cytotoxicity of cyanide, owing to the strong complexation tendency of metals and cyanide, inactivating live-essential metalloenzymes (Luque-Almagro et al., 2016). The removal of cyanide with adsorbents has been proven to be rather effective. Adsorbents are advantageous due to their low cost, insensitivity to cyanide's toxicity, inherent simplicity, and reusability. Removal of cyanide has been reported using sorbents from agricultural wastes, including nutshells, coconut husks, calcinated eggshells (Eletta et al., 2016), rice husks (Yazici et al., 2009), pistachios' green hulls (Moussavi & Khosravi, 2010), guar gum (Sharma, Kumar, Devi, et al., 2018), and by activated carbon (Singh & Balomajumder, 2016; Zhang et al., 2010) and activated carbon modified by TiO_2 (Ramírez-Muñiz et al., 2010).

As a result of their many advantageous properties, biopolymers like chitosan and gums have been intensively investigated (Bhatnagar & Sillanpää, 2009; Kumar et al., 2017; Sharma et al., 2018a; Sharma et al., 2018b). Compared to activated carbon, chitosan has a much greater concentration of hydroxyl groups on its surface, making it an excellent candidate for pollutant removal (Bhatnagar & Sillanpää, 2009). However, like all polysaccharides, it is not easy to remove it from the purified effluents (Reddy & Lee, 2013). Linking chitosan and other compounds to magnetic particles is a solution for environmental remediation, which allows for a simple, cheap, energy-efficient, and rapid water treatment (Donia et al., 2008; Hritcu et al., 2012; Moghaddam et al., 2020; Shadman et al., 2021; Tanhaei et al., 2015). Such magnetic sorbents can be removed from the solution using magnets. Iron oxide is most commonly used as the magnetic core for the preparation of such chitosan-based adsorbents (Pisanic et al., 2007), but other magnetic particle polymer combinations have been studied (Reddy & Lee, 2013). Iron oxides are unstable at low pH, which impairs their capability to be magnetically separated. Protecting the cores with an inert layer remedies this drawback whilst potentially providing another layer for improved sorption (Wang et al., 2010).

This study addresses the need for cost-effective and eco-friendly remediation techniques using a green-synthesized $NiFe_2O_4$-chitosan nanocomposite for cyanide removal. The study highlights the nanocomposite's potential as an effective and environmentally responsible adsorbent, offering an alternative to conventional treatments that frequently generate hazardous byproducts. The results contribute to more sustainable environmental protection strategies by providing insightful information on new cutting-edge materials for wastewater treatment.

Materials and Methods

Chemicals

Sodium cyanide (NaCN) and chitosan were acquired from Sigma–Aldrich Co (St. Louis, United States). All solvents were analytical grade and purchased from Merck Co. (Darmstadt, Germany). Hydrochloric acid (HCl, 37%), sodium hydroxide (NaOH, 99%), nickel chloride hexahydrate ($NiCl_2 \cdot 6H_2O$, 98%), ferric chloride hexahydrate ($FeCl_3 \cdot 6H_2O$, 98%), and glutaraldehyde (25% aqueous solution) were provided by Merck Co. (Darmstadt, Germany). Double-distilled deionized water (DDW) was used in all experiments and cleaning procedures unless mentioned otherwise. The concentrations of chemical solutions and their preparation methods are detailed in the respective synthesis sections.

Instruments

A JASCO 4600 series FT-IR spectrometer (Tokyo, Japan) was used for Fourier-transform infrared spectroscopy (FT-IR), conducted at room temperature with a scanning range of 400–4000 cm^{-1}, utilizing KBr pellets. X-ray diffraction (XRD) patterns were obtained using a Bruker AXS-D8 diffractometer (Billerica, Massachusetts, United States) with Cu-Kα_1 radiation (λ = 1.5406 Å) at a step size of 0.02° and a scanning rate of 1°/min. The microstructure of the synthesized composites was analyzed via scanning electron microscopy (SEM) and transmission electron microscopy (TEM) using a Philips CM-30 TEM (Eindhoven, Netherlands). The magnetic properties were assessed with a Lake Shore VSM model 7400 (Westerville, USA) under an applied field of ±10 kOe.

Synthesis of proposed green nanocomposite

Using mint extract as a natural reducing agent, a green synthesis method for $NiFe_2O_4$ nanoparticles is performed according to the literature with some modifications (Kalita et al., 2022). Fresh mint leaves (10 mg) were thoroughly washed with DDW and boiled in 100 mL of DDW at 80°C for 30 minutes, and the resulting extract was filtered using a Whatman No.1 filter paper and stored at 4°C for further use.

For green synthesis of $NiFe_2O_4$ nanoparticle, the solutions containing $NiCl_2.6H_2O$ (0.1 M) and $FeCl_3.6H_2O$ (0.2 M) were separately prepared in DDW (Kalita et al., 2022; Zeraatkar Moghaddam et al., 2018). Then, 50 mL of the mint extract was slowly added dropwise to the prepared solutions while stirring continuously. The mixture was subjected to 90°C for 2 hours to facilitate the reduction of metal ions and nanoparticle formation. Afterward, the precipitate was separated via centrifugation (6000 rpm, 10 min), washed with DDW to remove any remaining impurities, and dried at 100°C overnight. Ultimately, the obtained powder was calcined at 450°C for 2 hours to enhance crystallinity and structure integrity. This method offers an eco-friendly technique for producing $NiFe_2O_4$ nanoparticles, which may be utilized in water treatment and environmental remediation (Kalita et al., 2022; Zeraatkar Moghaddam et al., 2018).

After the $NiFe_2O_4$ was prepared and collected, 1.0 g of chitosan was dissolved in an 2% (v/v) aqueous acetic acid solution (Zeraatkar Moghaddam et al., 2018). Next, 0.5 g of the green synthesized NiFe2O4 nanoparticles were added and sonicated for 30 min to ensure uniform dispersion. Then, 5 mL of an aqueous 25% (w/v) glutaraldehyde solution was blended with the mixture to initiate gelation, followed by drying in a forced convection oven at 60°C overnight. Before grinding, the composite particle gels were washed several times with an aqueous acetic acid (2% (v/v)) solution and double distilled water, then dried at 50°C for another 12 hours (Tanhaei et al., 2015; Zeraatkar Moghaddam et al., 2018). They were kept under low humidity conditions in a desiccator to preserve the particles for further use.

Adsorption and desorption experiments

Adsorption experiments were conducted in batch mode, i.e., a defined amount of adsorbent (15-75 mg) and cyanide pollutant (100 to 200 $mg.L^{-1}$) was mixed in 10 mL water (temperature 25°C), whose pH-value was set to predefined values between 7 and 11 by 0.01 M HCl or NaOH aqueous solutions, depending on the experiment. The contact time was between 10 and 30 min under stirring at 800 rpm. After that, the adsorbents were separated from the remainder of the suspension, followed by quantification of the remaining cyanide in the solution. In all cases, titration was used to obtain cyanide concentrations (C), utilizing $AgNO_3$ (0.001M) and aqueous potassium iodide (10 g/L) solutions as indicators.

A similar approach was used in isothermal studies with cyanide concentrations between 10 and 500 $mg.L^{-1}$ and 60 minutes of contact time. In kinetic studies, 50 $mg.L^{-1}$ cyanide was used with contact times between 1 and 35 min with the other parameters at optimized values. After reaching equilibrium, removal efficiency and adsorption capacity values (qe and qt ($mg.\ g^{-1}$), respectively) were determined using Eqs. 3 and 4 (Sadeghi et al., 2015; Shadman et al., 2021; Tanhaei et al., 2015).

$$Cyanide\ removal\ (\%) = \frac{(C_0 - C_e)}{C_e} \times 100 \qquad (3)$$

$$q_e = \frac{(C_0 - C_e)V}{m} \text{ and } q_t = \frac{(C_0 - C_t)V}{m} \quad (4)$$

where Co (mg L-1), Ce (mg L-1), and Ct (mg L-1) stand, respectively, for the initial (o), equilibrium (e), and time-dependent (t) cyanide ion concentrations. m (g) stands for the mass of the proposed nanocomposite, and V (L) is the solution volume used.

Optimization of the treatment process

The adsorbent works reasonably well under most not-too-acidic conditions. However, major process factors were optimized, namely contact time, adsorbent dosage, initial pollutant concentration, and solution pH. Temperature (298 K) and stirring rate (800 rpm) were kept constant to ensure comparability. For efficient testing, we used CCD (Design Expert 10.0.0 (Stat-Ease Inc., Minneapolis, MN, USA)) to determine a minimum of experimental conditions to optimize the experimental design.

Results and Discussion

Characterization

FTIR results of the proposed green $NiFe_2O_4$-chitosan nanocomposite (Figure 1) show typical patterns for chitosan, namely the coinciding stretching vibrations of N–H and O–H (broad absorption peak at ~3400 cm-1), indicating the presence of hydroxyl (–OH) and amine ($–NH_2$) groups from chitosan. The broadness of the peak suggests hydrogen bonding interactions within the composite. The stretching vibrations band at ~2924 cm-1 is associated with the C–H stretching vibrations of aliphatic groups in chitosan, confirming the organic nature of the polymeric backbone. The peak at ~1640 represents the C=O stretching vibration from amide groups (amide I band) in chitosan. This peak suggests that the chitosan structure remains intact after the synthesis process. The C–N stretching vibrations, at ~1380 cm-1, further support the presence of chitosan within the nanocomposite. Moreover, a strong peak at ~1100 cm-1 shows the characteristic of the C–O–C stretching vibrations, confirming the glycosidic bond structure in chitosan. Finally, A prominent peak around 580 cm-1 is attributed to the Fe–O and Ni–O stretching vibrations, confirming the successful formation of $NiFe_2O_4$ nanoparticles. Thus, FTIR suggests the successful formation of nanocomposite consisting of nickel ferrite, chitosan, and glutaraldehyde.

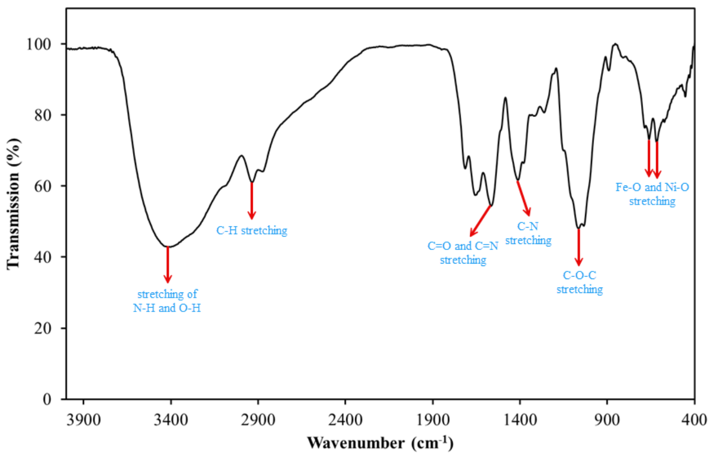

Fig 1. FTIR spectrum of proposed green $NiFe_2O_4$-chitosan nanocomposite.

A vibration sampling magnetometry (VSM) analysis of the green prepared NiFe2O4-chitosan nanocomposite shows a significant reduction in magnetization (see Fig. 2). Because glutaraldehyde cross-linked chitosan is non-magnetic, it forms an insulating layer around the magnetic core, limiting direct magnetic interactions. Despite this reduction in magnetization, the residual magnetic field remains sufficient to allow effective magnetic separation (see Fig. 2) (Jacob et al., 2011).

X-ray diffraction shows a rather complex pattern consisting of sharp peaks stemming from green NiFe2O4 (Kalita et al., 2022) (Figure. 3). The peaks at 2θ = 18.5°(111), 30.3°(220), 35.9°(311), 37.3°(222), 43.5°(400), 53.9°(422), 57.7°(511), and 63.1°(440) can be indexed to the Miller indices in the brackets behind the respective reflections according to JCPDS-card no. 10-0325 of cubic nickel ferrite. The observed peaks are at slightly higher 2θ than the JCPDS-reference (ca. 0.1°), which could be the consequence of the small size of the particles. In addition, a strong amorphous halo with two broad modes around 40° is prominent, which is typical for complex amorphous polymers and, thus, can be seen as the proof for the immobilization of chitosan and crosslinked glutaraldehyde on green NiFe2O4 (Kalita et al., 2022; Munir et al., 2021).

SEM image of green NiFe2O4-chitosan nanocomposite shown in Figure 4a shows porosity and agglomeration. A high-magnification image reveals interconnected nanoparticles, which increase surface area and provide more active sites for adsorption. As a result of the porous morphology observed, cyanide ions can be absorbed more effectively. Figure 4b shows the TEM image of a nanocomposite particle with a well-defined dark core (green NiFe2O4) and lighter outer layer (chitosan). An approximate 100 nm particle size confirms nanoscale dimensions. In this nanocomposite, the NiFe2O4 core is encapsulated by a polymeric layer, which stabilizes the nanocomposite while maintaining sufficient magnetization for easy separation.

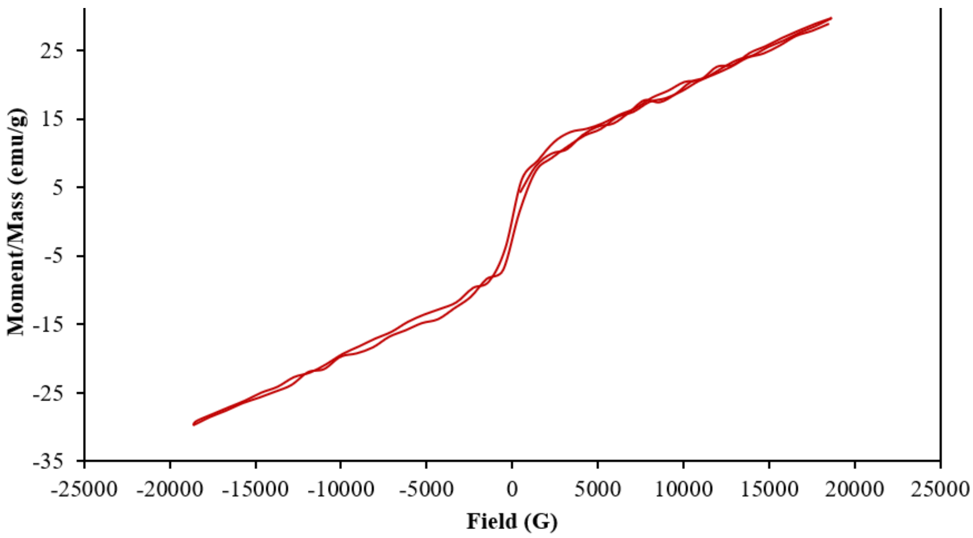

Fig 2. VSM data of the synthesized a) green $NiFe_2O_4$, and b) $NiFe_2O_4$-chitosan nanocomposite.

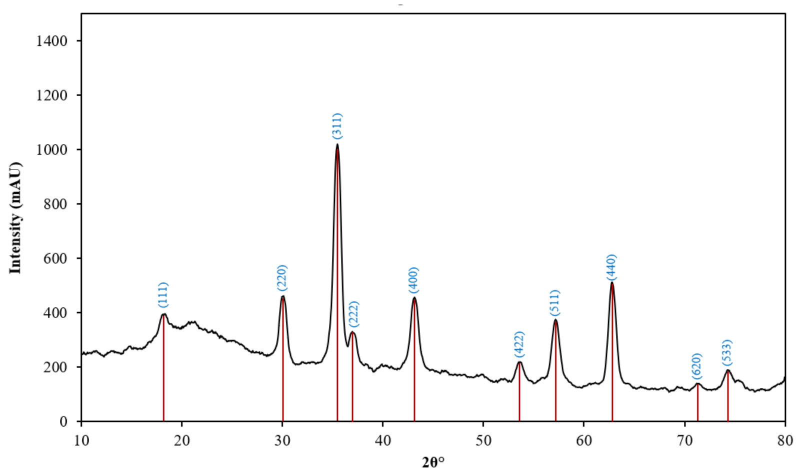

Fig 3. XRD pattern of the synthesized $NiFe_2O_4$-chitosan nanocomposite.

Experimental Design

In most experimental studies, univariate methods are used, i.e., an entire matrix of experiments is conducted, which means that many time-intensive and costly experiments are required. Furthermore, such a matrix approach does not assess variable interactions unless special advanced analysis techniques are used. A remedy to this predicament is multivariate techniques, which offer fast and efficient tools for optimizing several variables simultaneously. In this work, we use CCD, an independent quadratic design tool (Montgomery, 2019; Reece et al., 1993). The major influential parameters on cyanide adsorption are the amount of NiFe2O4-chitosan nanocomposite, contact time, pH, and initial cyanide concentration while keeping minor parameters (stirring rate, temperature) constant. These major parameters were systematically varied using a central composite design-based model to establish the parameter-performance surface, followed by variance analysis (ANOVA) to find the most relevant parameters and their predictions for the optimal parameter combination (Montgomery, 2019).

As the number of optimization parameters is small enough, a simple factorial design is sufficient, allowing for the application of CCD directly (Reece et al., 1993). To assess the number of required design points N, equation 5 is used.

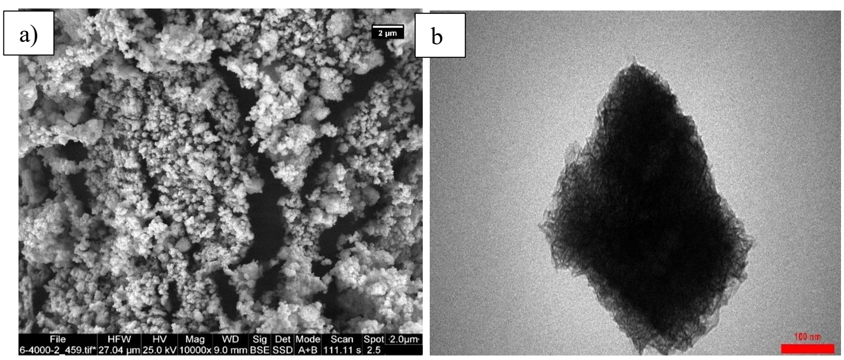

Fig 4. SEM and TEM images for the synthesized NiFe2O4-chitosan nanocomposite.

$$N = 2^k + 2k + N_0 \tag{5}$$

In this equation (Eq. 5), k stands for the number of input parameters, and N0 corresponds to the replicate number in the central design. Based on this equation, 36 experiments are required by the CCD, which were randomized in three blocks with four replicates per block. The values used for each of the four parameters are given in Table 1. The results of ANOVA and CCD analyses were found to be described by the quadratic polynomial, which reads as:

$$\mathrm{R}\,(\%) = +68.5 - 10.6\mathrm{A} + 13.4\mathrm{B} - 10.1\mathrm{C} + 3.5\mathrm{D} + 6.5\mathrm{AB} + 3.0\mathrm{BC} + 5.9\mathrm{A}^2 + 3.4\mathrm{C}^2 \tag{6}$$

Table 1. levels and experimental variables of the CCD.

Parameters	Levels				
	-α	-1	0	+1	+α
Initial pH (A)	7	8	9	10	11
Nanocomposite amount (mg) (B)	15	30	45	60	75
Initial concentration ($mg.L^{-1}$) (C)	12.5	25	37.5	50	62.5
Contact time (min) (D)	15	30	45	60	75

ANOVA analysis shows individual contributions from different sources to the overall experimental result variations. ANOVA results for cyanide removal in terms of their statistical significance parameters (P-values, the sum of the squares, and Fisher's F-ratios) can be found in Table 2. An F-value of 40.2 indicates a 0.01% chance of the observed result being due to statistical noise and signifies the high importance of the results (A. Asfaram et al., 2016). A p-value above 0.05 for the lack of fit suggests an excellent ability of Eq. 6 to fit the experimental data. Consequently, the quadratic A2 and C2 and the linear and interaction terms A, AB, B, BC, C, and D are statistically significant. The cyanide removal performance could be modeled with a high $R^2 = 0.9462$, showing an excellent agreement between modeled and experimental results. Moreover, the predicted $R^2 = 0.9260$ and the adjusted $R^2 = 0.8491$ conform well. Figure 5 shows the residual plot, indicating only a few percent deviations between modeled and experimental results. This shows the absence of considerable contradictions in the model, good experimental quality (low statistical scatter), and no violation of the initial assumptions. There is low statistical scatter in the residual plot (Figure 5), showing the model's high accuracy, denoted by an excellent signal-to-noise ratio > 4, indicating that the chosen method is efficient and appropriate (Asfaram et al., 2016)For our data, we found that the CCD's signal/noise ratio is an excellent 25.1, confirming that the model can be applied to the complete previously defined design space.

The results visualized with contour plots (Figure 6) give a clear and intuitive understanding of the correlations between adsorption and the various parameters (Montgomery, 2013). Both cyanide concentration and pH impact adsorption, i.e., greater cyanide loading and higher pH reduce adsorption. Contact time and nanoparticle adsorbent have a positive effect on adsorption, which is logical as the number of adsorption sites and a longer time for adsorption are beneficial, which is also the reason for the negative correlation between cyanide concentration and adsorption. The negative correlation between pH and adsorption in the investigated range could be due to weaker H-bonding and π-π interactions and, consequently, less likely adsorption. The reason for the reduction of these supramolecular interactions is plentiful hydroxyl groups on the green nanocomposite surface undergoing a negative transformation at higher pHs, thus leading to a lower affinity between them and cyanide.

Based on the CCD and ANOVA analysis, under the application of a non-linear optimization approach according to Nelder-Mead, the optimum parameters were found to be pH=8, 60 mg of green-prepared nanocomposite, and 60 min contact time to obtain an above 90% removal efficiency for a 50 $mg.L^{-1}$ cyanide solution. This agrees with the experiment, which found 93.0±7.1% vs. 91.7±6.2% in the model predicted (95% confidence level), showing excellent agreement between the experiment and the model.

Table 2. ANOVA table for modeling of the cyanide removal efficiency procedure.

	Sum of Square	Degree of Freedom	Mean Square	F-Value	p-Value
Block	220.8	2	110.4	2.9	0.0706
Model	12053.0	8	1506.6	40.2	0.0001
A	2703.0	1	2703.0	72.2	0.0001
B	4296.1	1	4296.1	114.7	0.0001
C	2454.3	1	2454.3	65.5	0.0001
D	291.9	1	291.9	7.8	0.0099
AB	669.5	1	669.5	17.9	0.0003
BC	145.8	1	145.8	3.9	0.0596
A^2	1115.9	1	1115.9	29.8	0.0001
C^2	376.5	1	376.5	10.0	0.0040
Residuals	936.3	25	37.4		
Lake of Fit	738.3	16	46.1	2.1	0.1304
Pure Error	197.8	9	22.0		
Cor Total	13279.6	35			

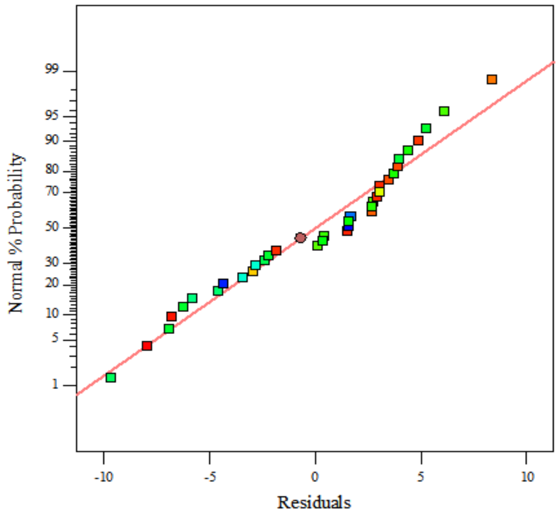

Fig 5. Normal plot of residuals for cyanide removal using the synthesized NiFe2O4-chitosan nanocomposite.

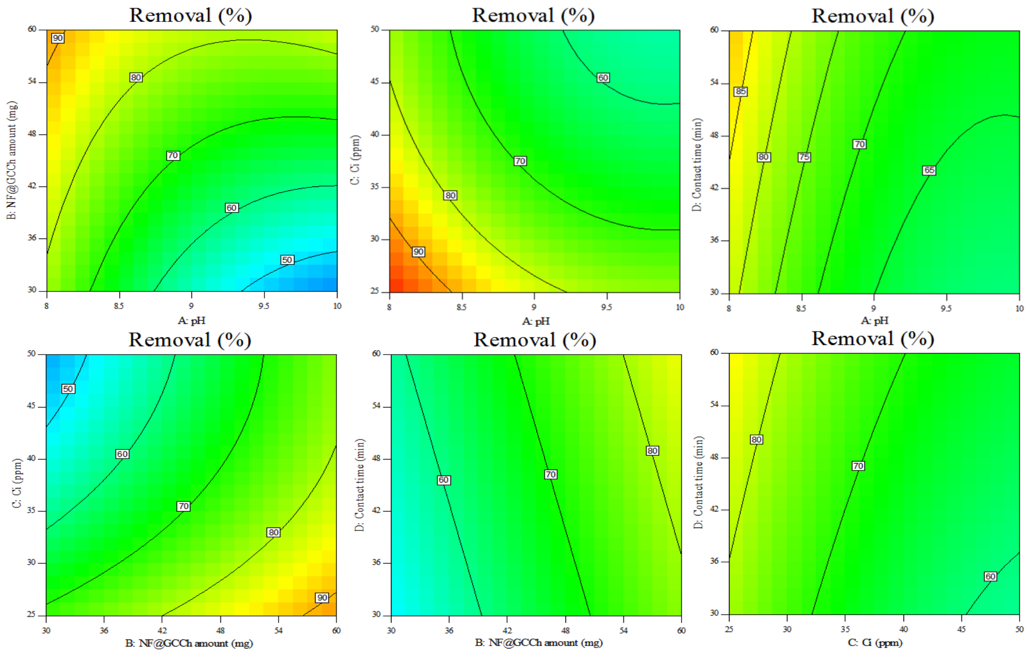

Fig 6. Contour plots, visualizing the effects of pH, nanocomposite amount, starting concentration, and contact time effects on efficiency of the adsorbent.

Adsorption isotherms

Further experiments were all done using the optimized conditions determined above. In addition to providing insight into how adsorbate interacts with adsorbent surfaces, adsorption isotherms can also contribute to determining adsorption efficiency and capacity. A variety of models have been used to describe adsorption behaviors in similar studies such as Langmuir, Freundlich, and Temkin (Gupta et al., 2012; Tanhaei et al., 2015). Analyzing the cyanide adsorption process on the synthesized nanocomposite was done using these models.

Adsorption isotherms were determined by varying the cyanide concentration (Figure 7) to gain a more in-depth insight into the physical-chemical processes behind this adsorption. For this purpose, the adsorption capacity was defined as Eq. 4.

In a linear-linear plot (Figure 7a) the data show a nonlinear behavior. Therefore, several classical adsorption models were also applied. Namely, the isotherm models according to Langmuir, Freundlich, and Temkin were used for the evaluation (Gupta et al., 2012; Tanhaei et al., 2015).

The Freundlich isotherm

The Freundlich isotherm model (see Eq. 7) assumes less material can be adsorbed when it is already covered with non-negligible amounts of adsorbed material.

$$\ln q_e = \ln k_f + \frac{1}{n} \ln C_e \qquad (7)$$

In this model, the key parameters of kf (adsorption capacity) and n (adsorption intensity) are the Freundlich constants (Gupta et al., 2012; Tanhaei et al., 2015). Here, qe ($mg.g^{-1}$) and Ce ($mg.L^{-1}$) refer to the equilibrium amount of removed cyanide and its equilibrium concentration in final treated solution, respectively. According to Table 3, the Freundlich model failed to adequately describe adsorption behavior, particularly at high and low concentrations

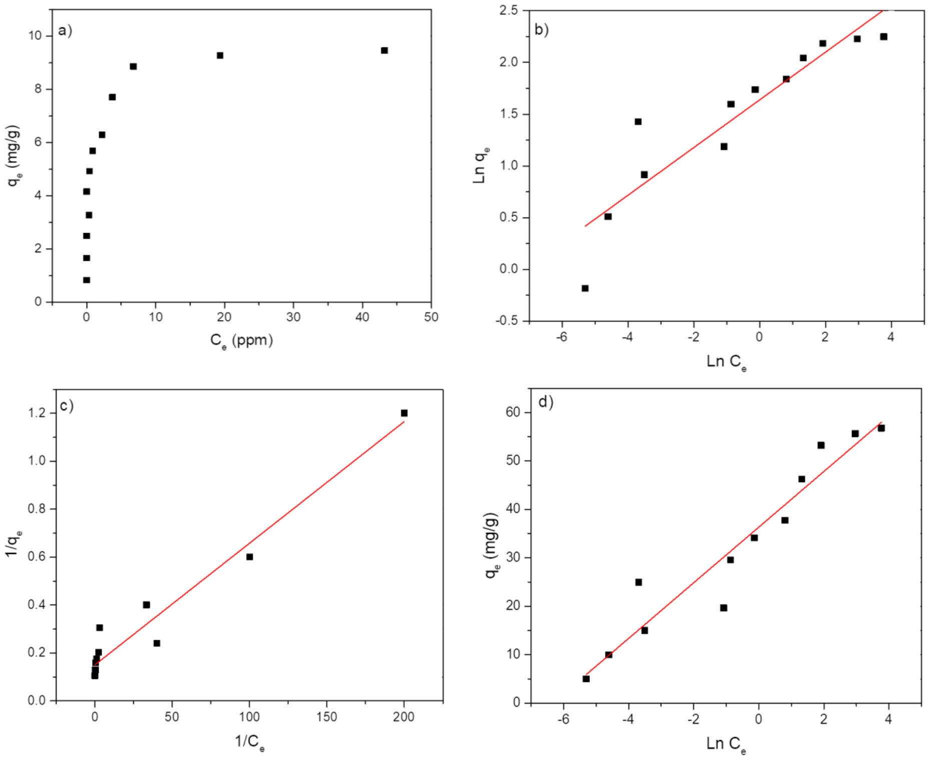

Fig 7. plots of the isotherm models; a) basic plot (qe vs. Ce), b) Freundlich model, c) Langmuir model, and d) Temkin model.

(R^2=0.8475). Even so, n = 4.3, the model parameters, indicated favorable adsorption (n > 1) (Gupta et al., 2012; Tanhaei et al., 2015).

Langmuir isotherm

The Langmuir isotherm assumes monolayer adsorption onto a surface with uniform adsorption sites and identical adsorption enthalpies for each site:

$$q_e = q_m \frac{bC_e}{1 + C_e} \quad (8)$$

where qm ($mg.g^{-1}$) is the maximum adsorption capacity, and b ($mL.mg^{-1}$) is the Langmuir constant. Typically, this equation (Eq. 8) is rearranged into linear form as follows:

$$\frac{1}{q_e} = \frac{1}{q_m} + \frac{1}{q_m b C_e} \quad (9)$$

In order to analyze adsorption favorability further, the parameter RL was calculated. For RL=0 it is irreversible, for 0 < RL< 1 it is favorable, for RL = 1 it is linear, and for RL> 1 it is unfavorable (Tanhaei et al., 2015).

$$R_L = \frac{1}{1 + bC_0} \quad (10)$$

where C0 represents the initial cyanide concentration. 60 mg of the nanocomposite was incorporated into a 10 mL solution to study cyanide adsorption at concentrations ranging from 5 to 100 $mg.L^{-1}$ (Table 3). RL value of 0.2485 and excellent fit (R^2=0.9532) indicate favorable adsorption. Langmuir's superior fit suggests monolayer adsorption with homogeneous active sites, which is the most suitable model for explaining cyanide adsorption on synthesized nanocomposite.

Table 3. Adsorption parameters of cyanide by proposed nanocomposite for Langmuir, Freundlich, and Temkin models.

T (K)	Langmuir constant				Freundlich constant			Temkin constant		
298	q_m	K_L	R_L	R^2	n	K_f	R^2	b_T	K_T	R^2
	6.6	29.57	0.2485	0.9532	4.3	5.15	0.8475	431.53	311.47	0.9242

The Temkin isotherm

According to the Temkin isotherm, the enthalpy of adsorption decreases linearly with surface coverage because adsorption sites are not identical (Anbia & Salehi, 2012; Tanhaei et al., 2017). This can be expressed as follows:

$$q_e = \frac{RT}{b_T} \ln(K_{Te} C_e) \quad (11)$$

where T (K) is temperature, R = 8.314 J/(mol·K) is the gas constant, KTe ($L \cdot g^{-1}$) is the Temkin equilibrium binding constant, and bT ($J \cdot mol^{-1}$) is the heat of adsorption (Asfaram et al., 2017; Tanhaei et al., 2017). It is often expressed as a linear equation:

$$q_e = A + B \ln C_e, \quad A = \frac{RT}{b_T} \ln K_{Te}, \quad \text{and } B = \frac{RT}{b_T} \quad (12)$$

With an R^2 = 0.9242, the Temkin model fit the data, but the obtained parameters indicated that the adsorption enthalpy did not decrease significantly with surface coverage. It is evident that adsorption sites remain available even at high concentrations, confirming that the Langmuir model provides the most accurate description of adsorption.

Comparison of Isotherm Models

A summary of the adsorption parameters is provided in Table 3. The Langmuir isotherm showed the best fit (R^2 = 0.9532), suggesting monolayer adsorption on a homogeneous surface. Accordingly, the nanocomposite's adsorption sites are uniform, and the maximum adsorption capacity was not reached within the studied range, confirming the material's high cyanide removal efficiency.

Kinetic studies

Identifying the mechanism and rate-controlling steps of the cyanide adsorption process requires understanding the adsorption kinetics. In order to analyze the kinetic behavior, two commonly used models were applied: pseudo-first-order and pseudo-second-order.

Pseudo-first-order model

According to the pseudo-first-order model (Wu et al., 2001), the rate of adsorption depends on the difference between equilibrium adsorption capacity (qe) and the amount of adsorbate adsorbed at time t. As the most straightforward model, a first-order model

$$\frac{dq}{dt} = k_1(q_e - q_t) \quad (13)$$

which was integrated to form (Wu et al., 2001).

$$\log(q_e - q_t) = \log q_e - \frac{k_1 t}{2.303} \quad (14)$$

Using eq. 13, the plot of log (q_e–q^t) versus time (Figure 8) resulted in a first-order rate constant of k_1=0.0069 min^{-1} with a calculated q_e = 2.25 mg.g^{-1} which was determined for a 50 mg.L^{-1} initial cyanide concentration (see Table 4 and Figure 8a). This model, however, fails to adequately describe the experimental data based on the correlation coefficient R^2 = 0.7185. Figure 8a confirms this visually, indicating that the adsorption process is not pseudo-first-order.

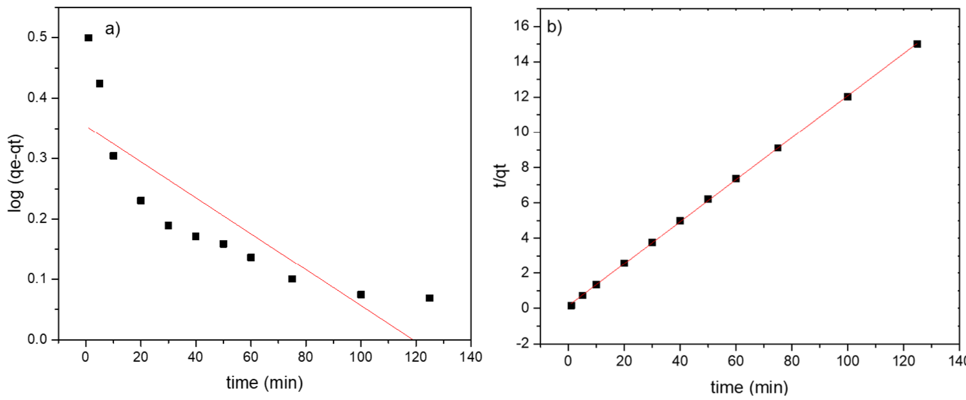

Fig 8. a) Pseudo-first-order and b) pseudo-second-order kinetic models for cyanide adsorption on proposed nanocomposite.

Table 4. Kinetics parameters for cyanide removal by proposed nanocomposite.

Time range (min)	C_0 (mg.L^{-1})	Pseudo first order			Pseudo second order		
		q_e (mg.g^{-1})	k_1 (min^{-1})	R^2	q_e (mg.g^{-1})	k_1 (min^{-1})	R^2
1-125	50	2.25	0.0069	0.7185	8.39	0.0887	0.9998

Pseudo-second-order model

In order to improve the kinetic description, a pseudo-second-order model was used. This model assumes that chemisorption, involving valency forces through electron sharing or exchange, is the rate-limiting step (Ho & McKay, 2000). The pseudo-second-order model, defined as

$$\frac{dq}{dt} = k_2(q_e - q_t)^2 \quad (15)$$

was integrated from q = 0 to qt at t = 0 to t0 yields

$$\frac{1}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e} \quad (16)$$

In this model, k_2 (g.mg^{-1}.min^{-1})) is the second-order rate constant. A plot of t/q_t versus t (Figure 8b) provided a straight line with R^2 = 0.9998, confirming an excellent fit to the experimental data (see Table 4 and Figure 8b).

$$h = k_2 {q_e}^2 \quad (17)$$

The calculated equilibrium adsorption capacity was q_e = 8.39 mg·g^{-1}, which is very close to the experimentally observed value. This suggests that the pseudo-second-order model reliably describes the adsorption mechanism. Based on the good agreement with this model, the adsorption process is controlled by chemisorption, as in other studies on cyanide removal using nanocomposite materials (Rezaei et al., 2018; Tanhaei et al., 2015). Furthermore, it indicates that NiFe2O4 and chitosan nanocomposites have a strong affinity for cyanide ions.

Comparison of Kinetic Models

As shown in Table 4, the pseudo-second-order model offers a better fit than the pseudo-first-order model based on the kinetic parameters. This suggests that adsorption involves surface interactions and chemical bonding, rather than simple physical adsorption. The initial fast uptake followed by slower adsorption over time is consistent with other reports on chemisorptive processes (Gupta et al., 2012; Ho & McKay, 2000).

Comparison of Adsorbents for Cyanide Removal

According to Table 5, the GNF@GCCs synthesized in this study demonstrated an adsorption capacity of 8.4 $mg.g^{-1}$ at pH 8–9, which is comparable to conventional adsorbents such as activated carbon (7.0 mg.g-1, (Monser & Adhoum, 2002)) or granular activated carbon (7.9 mg/g^{-1}, (Dash et al., 2009b)). It may be environmentally and economically unfavorable to use heavy metals in certain metal-impregnated carbons, such as Cu-impregnated or Ag-impregnated activated carbon (Baghel et al., 2006; Barakat, 2005; Deveci et al., 2006; Monser & Adhoum, 2002).
GNF@GCCs nanocomposite offers a sustainable alternative through eco-friendly synthesis, magnetic separability, and biocompatibility. As a result of its moderate adsorption capacity, ease of separation, and environmental safety, it is an ideal cyanide remover for real-world applications.

Conclusion

A novel hybrid nanocomposite of green synthesized nickel ferrite (NF) coated with cross-linked chitosan as a cost-effective and eco-friendly adsorbent has been developed to remove cyanide from aqueous media. The bath adsorption experimental results demonstrated that the proposed GNF@GCCs nanocomposite exhibited exceptionally high cyanide removal efficiency at intermediate pH, making it suitable for practical water and wastewater treatments. The process reached adsorption equilibrium, with removal efficiencies above 95%, within 60 minutes, indicating its potential for real-time water and wastewater treatment. The central composite design (CCD) and ANOVA provided a robust statistical framework for optimizing the process parameters, achieving maximum cyanide removal efficiency, and a high correlation coefficient (R^2 = 0.9462). Moreover, response surface 3D plots were used to

Table 5. Comparison of the proposed GNF@GCCs with other adsorbents

Adsorbent	Adsorption capacity ($mg.g^{-1}$)	Sample pH	Reference
Activated carbon	7.0	11	(Monser & Adhoum, 2002)
Granular activated carbon	7.9	9	(Dash et al., 2009b)
TiO_2	13.0	7	(Barakat, 2005)
Ni-impregnated activated carbon	15.4	11	(Monser & Adhoum, 2002)
Cu(II)-impregnated activated carbon	16.6	10.5	(Baghel et al., 2006)
Cu-impregnated activated carbon	19.7	10.5-11	(Deveci et al., 2006)
Ag-impregnated activated carbon	26.5	11	(Monser & Adhoum, 2002)
GNF@GCCs	8.4	8-9	This study

illustrate the influence of key parameters on removal efficiency, aiding in the adsorption process optimization. The process reached adsorption equilibrium after 60 minutes for a sample containing 10 mL of 50 mg.L^{-1} cyanide at pH 8 with only 60 mg of GNF@GCCs, making it sufficiently rapid for practical application. The Langmuir isotherm model best fitted the data, confirming monolayer cyanide adsorption on a homogeneous GNF@ GCCs surface. The kinetic data showed a well-fitting with a pseudo-second-order kinetic model, suggesting an initial rapid adsorption phase followed by gradual internal diffusion. Overall, this study demonstrates the effectiveness of the NF-chitosan nanocomposite as a sustainable and highly efficient adsorbent for cyanide removal, providing a viable alternative to conventional treatment methods while minimizing secondary pollution and operational costs.

References

Anbia, M. & Salehi, S. (2012). Removal of acid dyes from aqueous media by adsorption onto amino-functionalized nanoporous silica SBA-3. *Dyes and Pigments*, 94(1), 1–9. https://doi.org/10.1016/j.dyepig.2011.10.016

Asfaram, A., Ghaedi, M., Azqhandi, M. H. A., Goudarzi, A. & Dastkhoon, M. (2016). Statistical experimental design, least squares-support vector machine (LS-SVM) and artificial neural network (ANN) methods for modeling the facilitated adsorption of methylene blue dye. *RSC Advances*, 6(46), 40502–40516. https://doi.org/10.1039/c6ra01874b

Asfaram, Arash, Ghaedi, M., Ahmadi Azqhandi, M. H., Goudarzi, A. & Hajati, S. (2017). Ultrasound-assisted binary adsorption of dyes onto Mn@ CuS/ZnS-NC-AC as a novel adsorbent: Application of chemometrics for optimization and modeling. *Journal of Industrial and Engineering Chemistry*, 54. https://doi.org/10.1016/j.jiec.2017.06.018

Baghel, A., Singh, B., Pandey, P., Dhaked, R. K., Gupta, A. K., Ganeshan, K. & Sekhar, K. (2006). Adsorptive removal of water poisons from contaminated water by adsorbents. *Journal of Hazardous Materials*, 137(1), 396–400. https://doi.org/10.1016/j.jhazmat.2006.02.070

Barakat, M. A. (2005). Adsorption behavior of copper and cyanide ions at TiO2-solution interface. *Journal of Colloid and Interface Science*, 291(2), 345–352. https://doi.org/10.1016/j.jcis.2005.05.047

Beasley, D. M. G. & Glass, W. I. (1998). Cyanide poisoning: pathophysiology and treatment recommendations. *Occupational Medicine*, 48(7), 427–431. https://doi.org/10.1093/OCCMED/48.7.427

Bhatnagar, A. & Sillanpää, M. (2009). Applications of chitin- and chitosan-derivatives for the detoxification of water and wastewater - A short review. In *Advances in Colloid and Interface Science,* 152(1–2), 26–38. https://doi.org/10.1016/j.cis.2009.09.003

Chang, E. E., Hsing, H. J., Chiang, P. C., Chen, M. Y. & Shyng, J. Y. (2008). The chemical and biological characteristics of coke-oven wastewater by ozonation. *Journal of Hazardous Materials*, *156*(1–3), 560–567. https://doi.org/10.1016/j.jhazmat.2007.12.106

Dash, R. R., Gaur, A. & Balomajumder, C. (2009a). Cyanide in industrial wastewaters and its removal: A review on biotreatment. *Journal of Hazardous Materials,* 163(1), 1–11. https://doi.org/10.1016/j.jhazmat.2008.06.051

Dash, R. R., Balomajumder, C. & Kumar, A. (2009b). Removal of cyanide from water and wastewater using granular activated carbon. *Chemical Engineering*

Journal, 146(3), 408–413. https://doi.org/10.1016/j.cej.2008.06.021

Deveci, H., Yazici, E. Y., Alp, I. & Uslu, T. (2006). Removal of cyanide from aqueous solutions by plain and metal-impregnated granular activated carbons. *International Journal of Mineral Processing*, *79(3),* 198–208. https://doi.org/10.1016/j.minpro.2006.03.002

Donia, A. M., Atia, A. A. & Elwakeel, K. Z. (2008). Selective separation of mercury(II) using magnetic chitosan resin modified with Schiff's base derived from thiourea and glutaraldehyde. *Journal of Hazardous Materials*, 151(2–3), 372–379. https://doi.org/10.1016/j.jhazmat.2007.05.083

Douglas C. Montgomery. (2019). Design and Analysis of Experiments, 10th Edition | Wiley. In *Wiley*.

Eletta, O. A. A., Ajayi, O. A., Ogunleye, O. O. & Akpan, I. C. (2016). Adsorption of cyanide from aqueous solution using calcinated eggshells: Equilibrium and optimisation studies. *Journal of Environmental Chemical Engineering*, *4*(1), 1367–1375. https://doi.org/10.1016/j.jece.2016.01.020

Gracia, R. & Shepherd, G. (2004). Cyanide poisoning and its treatment. *pharmacotherapy: The Journal of Human Pharmacology and Drug Therapy*, 24(10), 1358–1365. https://doi.org/10.1592/PHCO.24.14.1358.43149

Gupta, V. K., Ganjali, M. R., Nayak, A., Bhushan, B. & Agarwal, S. (2012). Enhanced heavy metals removal and recovery by mesoporous adsorbent prepared from waste rubber tire. *Chemical Engineering Journal*, 197, 330–342. https://doi.org/10.1016/j.cej.2012.04.104

Hassani, G., Nasseri, S. & Gharibi, H. (2011). Removal of cyanide by electrocoagulation process. *Analytical and Bioanalytical Electrochemistry*, *3*(6), 625–634.

Hendry-Hofer, T. B., Ng, P. C., Witeof, A. E., Mahon, S. B., Brenner, M., Boss, G. R. & Bebarta, V. S. (2019). A review on ingested cyanide: risks, clinical presentation, diagnostics, and treatment challenges. *Journal of Medical Toxicology*, 15(2), 128–133. https://doi.org/10.1007/S13181-018-0688-Y/METRICS

Ho, Y. S. & McKay, G. (2000). The kinetics of sorption of divalent metal ions onto sphagnum moss peat. *Water Research*, 34(3), 735–742. https://doi.org/10.1016/S0043-1354(99)00232-8

Hritcu, D., Humelnicu, D., Dodi, G. & Popa, M. I. (2012). Magnetic chitosan composite particles: Evaluation of thorium and uranyl ion adsorption from aqueous solutions. *Carbohydrate Polymers*, *87*(2), 1185–1191. https://doi.org/10.1016/j.carbpol.2011.08.095

Jacob, B. P., Kumar, A., Pant, R. P., Singh, S. & Mohammed, E. M. (2011). Influence of preparation method on structural and magnetic properties of nickel ferrite nanoparticles. *Bulletin of Materials Science*, 34(7), 1345–1350. https://doi.org/10.1007/s12034-011-0326-7

Kalita, C., Boruah, P. K., Das, M. R. & Saikia, P. (2022). Facile green synthesis of nickel-ferrite-rGO (NiFe2O4/rGO) nanocomposites for efficient water purification under direct sunlight. *Inorganic Chemistry Communications*, 146, 110073. https://doi.org/10.1016/J.INOCHE.2022.110073

Kumar, A., Naushad, M., Rana, A., Inamuddin, Preeti, Sharma, G., Ghfar, A. A., Stadler, F. J. & Khan, M. R. (2017). ZnSe-WO3 nano-hetero-assembly stacked on Gum ghatti for photo-degradative removal of Bisphenol A: Symbiose of adsorption and photocatalysis. *International Journal of Biological Macromolecules*, *104*, 1172–1184. https://doi.org/10.1016/j.ijbiomac.2017.06.116

Kuyucak, N. & Akcil, A. (2013). Cyanide

and removal options from effluents in gold mining and metallurgical processes. In *Minerals Engineering,* 50-51,13-29. https://doi.org/10.1016/j.mineng.2013.05.027

Luque-Almagro, V. M., Moreno-Vivián, C. & Roldán, M. D. (2016). Biodegradation of cyanide wastes from mining and jewellery industries. In *Current Opinion in Biotechnology,* 38, 9–13. https://doi.org/10.1016/j.copbio.2015.12.004

Moghaddam, A. Z., Jazi, M. E., Allahrasani, A., Khazaei, M., Ganjali, M. R., Saeb, M. R. & Vatanpour, V. (2020). Removal of Chromate and Nitrate Ions from Aqueous Solutions by CoxFe3-xO4@ silica Hybrid Nanoparticles Decorated with Cross-Linked Tragacanth Gum: Experiment, Modeling and Optimization. *ChemistrySelect*, *5*(18), 5404–5413. https://doi.org/10.1002/SLCT.202000725

Monser, L. & Adhoum, N. (2002). Modified activated carbon for the removal of copper, zinc, chromium and cyanide from wastewater. *Separation and Purification Technology*, *26*(2–3), 137–146. https://doi.org/10.1016/S1383-5866(01)00155-1

Montgomery, D. C. (2013). Design and analysis of experiments (international student version). *John Wiley & Sons, Inc*. https://doi.org/10.1198/tech.2006.s372

Moussavi, G. & Khosravi, R. (2010). Removal of cyanide from wastewater by adsorption onto pistachio hull wastes: Parametric experiments, kinetics and equilibrium analysis. *Journal of Hazardous Materials*, *183*(1–3), 724–730. https://doi.org/10.1016/j.jhazmat.2010.07.086

Munir, S., Farooq Warsi, M., Zulfiqar, S., Ayman, I., Haider, S., Alsafari, I. A., Agboola, P. O. & Shakir, I. (2021). Nickel ferrite/zinc oxide nanocomposite: Investigating the photocatalytic and antibacterial properties. *Journal of Saudi Chemical Society*, *25*(12), 101388. https://doi.org/10.1016/J.JSCS.2021.101388

Pisanic, T. R., Blackwell, J. D., Shubayev, V. I., Fiñones, R. R. & Jin, S. (2007). Nanotoxicity of iron oxide nanoparticle internalization in growing neurons. *Biomaterials*, *28*(16), 2572–2581. https://doi.org/10.1016/j.biomaterials.2007.01.043

Pulkka, S., Martikainen, M., Bhatnagar, A. & Sillanpää, M. (2014). Electrochemical methods for the removal of anionic contaminants from water - A review. In *Separation and Purification Technology.* 132,252-271. https://doi.org/10.1016/j.seppur.2014.05.021

Ramírez-Muñiz, K., Song, S., Berber-Mendoza, S. & Tong, S. (2010). Adsorption of the complex ion Au(CN)2- onto sulfur-impregnated activated carbon in aqueous solutions. *Journal of Colloid and Interface Science*, *349*(2), 602–606. https://doi.org/10.1016/j.jcis.2010.05.056

Reddy, D. H. K. & Lee, S. M. (2013). Application of magnetic chitosan composites for the removal of toxic metal and dyes from aqueous solutions. *Advances in Colloid and Interface Science*, *201–202*, 68–93. https://doi.org/10.1016/j.cis.2013.10.002

Reece, J. E., Deming, S. N. & Morgan, S. L. (1993). Experimental design: a chemometric approach. in *elsevier*.

Rezaei, R., Massinaei, M. & Zeraatkar Moghaddam, A. (2018). Removal of the residual xanthate from flotation plant tailings using modified bentonite. *Minerals Engineering*, *119*, 1–10. https://doi.org/10.1016/j.mineng.2018.01.012

Sadeghi, S., Moghaddam, A. Z. & Massinaei, M. (2015). Novel tunable composites based on bentonite and modified tragacanth gum for removal of acid dyes from aqueous solutions. *RSC Advances*, *5*(69), 55731–55745. https://doi.org/10.1039/c5ra07979a

Scarazzato, T., Buzzi, D. C., Bernardes, A. M. & Romano Espinosa, D. C. (2015).

Treatment of wastewaters from cyanide-free plating process by electrodialysis. *Journal of Cleaner Production*, *91*, 241–250. https://doi.org/10.1016/j.jclepro.2014.12.046

Shadman, S., Massinaei, M. & Zeraatkar Moghaddam, A. (2021). Removal of cyanide from the gold cyanidation plant tailings using graphene-based magnetic nanocomposites. *Chemical Papers*, *75*(10), 5543–5560. https://doi.org/10.1007/s11696-021-01678-9

Sharma, G., Kumar, A., Devi, K., Sharma, S., Naushad, M., Ghfar, A. A., Ahamad, T. & Stadler, F. J. (2018a). Guar gum-crosslinked-Soya lecithin nanohydrogel sheets as effective adsorbent for the removal of thiophanate methyl fungicide. *International Journal of Biological Macromolecules*, 114, 295–305. https://doi.org/10.1016/j.ijbiomac.2018.03.093

Sharma, G., Kumar, A., Naushad, M., García-Peñas, A., Al-Muhtaseb, A. H., Ghfar, A. A., Sharma, V., Ahamad, T. & Stadler, F. J. (2018b). Fabrication and characterization of Gum arabic-cl-poly(acrylamide) nanohydrogel for effective adsorption of crystal violet dye. *Carbohydrate Polymers*, 202, 444–453. https://doi.org/10.1016/j.carbpol.2018.09.004

Singh, N. & Balomajumder, C. (2016). Simultaneous removal of phenol and cyanide from aqueous solution by adsorption onto surface modified activated carbon prepared from coconut shell. *Journal of Water Process Engineering*, *9*, 233–245. https://doi.org/10.1016/j.jwpe.2016.01.008

Tanhaei, B., Ayati, A., Lahtinen, M. & Sillanpää, M. (2015). Preparation and characterization of a novel chitosan/Al2O3/magnetite nanoparticles composite adsorbent for kinetic, thermodynamic and isotherm studies of Methyl Orange adsorption. *Chemical Engineering Journal*, 259, 1–10. https://doi.org/10.1016/j.cej.2014.07.109

Tanhaei, B., Ayati, A., Bamoharram, F. F. & Sillanpää, M. (2017). Magnetic EDTA functionalized preyssler cross linked chitosan nanocomposite for adsorptive removal of pb(ii) ions. *Clean - Soil, Air, Water*, 45(10), 1700328. https://doi.org/10.1002/clen.201700328

Wang, J., Zheng, S., Shao, Y., Liu, J., Xu, Z. & Zhu, D. (2010). Amino-functionalized Fe3O4@SiO2 core-shell magnetic nanomaterial as a novel adsorbent for aqueous heavy metals removal. *Journal of Colloid and Interface Science*, *349*(1), 293–299. https://doi.org/10.1016/j.jcis.2010.05.010

Wu, F. C., Tseng, R. L. & Juang, R. S. (2001). Kinetic modeling of liquid-phase adsorption of reactive dyes and metal ions on chitosan. *Water Research*, *35*(3), 613–618. https://doi.org/10.1016/S0043-1354(00)00307-9

Yazici, E. Y., Deveci, H. & Alp, I. (2009). Treatment of cyanide effluents by oxidation and adsorption in batch and column studies. *Journal of Hazardous Materials*, 166(2–3), 1362–1366. https://doi.org/10.1016/j.jhazmat.2008.12.050

Zeraatkar Moghaddam, A., Ghiamati, E., Pourashuri, A. & Allahresani, A. (2018). Modified nickel ferrite nanocomposite/functionalized chitosan as a novel adsorbent for the removal of acidic dyes. *International Journal of Biological Macromolecules*, *120*, 1714–1725. https://doi.org/10.1016/j.ijbiomac.2018.09.198

Zhang, W., Liu, W., Lv, Y., Li, B. & Ying, W. (2010). Enhanced carbon adsorption treatment for removing cyanide from coking plant effluent. *Journal of Hazardous Materials*, 184(1–3), 135–140. https://doi.org/10.1016/j.jhazmat.2010.08.015

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Correlation of chlorophyll fluorescence parameter Fv/Fm with physiological development and grain yield in local wheat cultivars (*Triticum aestivum L.*) under water deficit stress in south Iraq

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Abstract

This investigation aims to reveal the physiological responses of two local wheat cultivars (*Triticum aestivum L.*) to grain yield strived under the extreme conditions of desert environments. In arid and semi-arid regions where contemporary civilization relies on agriculture, we used a Chlorophyll Fluorometer linked to the WinControl-3 software, which enabled us to monitor the health status of the plant accurately. Conventional methods of assessing the health of the crops are beneficial to endeavor, but an infusion of technology as such enables effective resource management while increasing the efficiency of monitored physiological changes. We noted that with critical modular water deficit stress during vital stages of development, there is not a marked reduction in grain yield. The yield data collected at the end of April for the BUHOTH 22 cultivar reveals that the yield for the 6-day irrigation interval was 552 g/m², resulting in a total of 1380 kg for 2500 m². The parameter of fluorescence Fv/Fm was found to be the most important marker able to differentiate the physiological state over a period of time. This parameter is significant as it raises the standard of care and management of plants and determines the optimum irrigation proviso for arid regions, improving the yield of such areas. This study highlights the link between physiological changes in the plant life cycle and grain yield under water deficiency, emphasizing the need to integrate these physiological components into agricultural management strategies. Identifying these correlations enables farmers to swiftly address challenges in their work.

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Introduction

Wheat (*Triticum aestivum* L.) is one of the most widely cultivated cereal crops globally, serving as a fundamental source of nutrition for billions of people. With a cultivation history that spans thousands of years, wheat provides essential carbohydrates, proteins, and dietary fiber, making it a staple food in many cultures (Khalid et al., 2023). The growth and productivity of wheat are significantly affected by environmental factors, including temperature, humidity, and soil conditions (Huang et al., 2024). However, various abiotic stresses, particularly water scarcity, pose substantial challenges to wheat cultivation, especially in arid and semi-arid areas such as South Iraq. Drought stress is a critical factor that adversely affects the growth, development, and reproductive success of wheat. The interaction of climate, soil quality, and environmental stressors can lead to reduced yields and compromised crop quality (Zia et al., 2021). In South Iraq, where water resources are limited and rainfall is erratic, the impact of drought on wheat production is particularly pronounced. Traditional agricultural systems such as irrigation, soil reclamation, and the application of fertilizers have been employed to mitigate these challenges. However, as water scarcity becomes increasingly severe due to climate change, there is a pressing need to find out sustainable agricultural practices that can enhance the resilience of wheat crop. In recent decades, there has been a growing interest in the development of genetically tolerance wheat varieties, driven by the need for sustainable agricultural techniques that can withstand the pressures of climate change and resource scarcity (Yanagi, 2024). Breeding programs focused on drought tolerance aim to identify and incorporate traits that enable wheat to thrive under water-limited conditions. Among these traits, the chlorophyll fluorescence parameter Fv/Fm has emerged as a valuable indicator of photosynthetic efficiency and overall plant health, particularly under stress conditions. Understanding the relationship between Fv/Fm and physiological progress is essential for assessing the adaptability of local wheat cultivars to water deficit stress (Bartold and Kluczek, 2024). The Fv/Fm ratio reflects the maximum quantum efficiency of photosystem II, providing insights into the plant's ability to perform photosynthesis efficiently under drought stress conditions. Research has shown that variations in this parameter can correlate with other physiological traits, such as water absorption and transpiration efficiency, which are critical for drought stress tolerance (Hu et al., 2023). The physiological status of wheat plants, allowing for better management strategies under water deficit stress. Environmental stressors, particularly water deficit stress, are prevalent in agricultural landscapes. Water evaporation occurs when crop water uptake is insufficient to meet atmospheric demands, which is governed by root characteristics, soil properties, and atmospheric conditions affecting crop evapotranspiration (Nabhan et al., 2020). Grain yield serves as a key indicator of drought resistance, with genotype phenology also playing a significant role in wheat's yield potential under drought stress conditions (Ahmed et al., 2020). Understanding how these factors interact is crucial for developing effective management practices that can enhance wheat productivity in water-limited environments. Desert conditions present unique physiological challenges for wheat production, characterized by intense sunlight and elevated temperatures. Crop evapotranspiration (ET), particularly transpiration, is inversely related to grain yield in both C_3 and C_4 plants under low humidity conditions (Wang et al., 2023). Water deficit stress significantly reduces grain yield, particularly when crop cover is incomplete, which leads to increased soil water evaporation. Effective crop management practices are essential for enhancing grain yield in dryland agriculture, as soil water evaporation can account for more than 50% of ET (Yu et al., 2021). The harvest index, influenced by transpiration during the grain-filling period and the prevailing transpiration efficiency, indicates that maximizing yield potential requires careful management of water resources, particularly during critical growth stages (Yadav et al., 2024).The aim of this research is to investigate the correlation between the chlorophyll fluorescence parameter Fv/Fm, physiological aspects, and grain yield under water deficit stress conditions in local wheat cultivars (*Triticum aestivum* L.) in South Iraq. By focusing on the adoption of drought-tolerance wheat variety (BHOUTH 22) and efficient irrigation methods, this study seeks to provide actionable insights for farmers in the region.

Materials and Methods

Study Area:

The study area is located in the Basra province of Iraq, within the city of Zubair Al-Luhais, at geographical coordinates 30° 34’ 08” N and 46° 58’ 14” E, with average minimum temperature is around 14^0C and the average maximum temperature is around 27^0C. Spanning a total area of 0.25 hectares (2500 m²), this region is characterized by its sandy loam soil, which is renowned for its favorable drainage and nutrient-holding capacity, making it well-suited for diverse agricultural practices. The soil exhibits an electrical conductivity of 2.5 dS/m, indicating a moderate level of salinity, while the electrical conductivity of the water is recorded at 9.1 dS/m, suggesting the presence of soluble salts that could influence crop growth. The soil pH was measured at 7.61, which lies within the optimal range for many crops, thereby promoting nutrient availability and microbial activity.

Experiments:

To enhance organic matter, 50 kg of cow manure was applied across the 2500 m² area on November 1, 2023, enriching the soil with essential nutrients and improving its structure. Fertilization practices were carefully planned and implemented to enhance soil fertility and promote crop development. On November 23, 2023, 25 kg of DAP (Diammonium Phosphate) fertilizer per 2500 m² was applied using mechanical sowing methods, providing a quick source of phosphorus and nitrogen to the plants. This was followed by two applications of urea fertilizer on December 15, 2023; the first part consisted of 25 kg, and the second part included 40 kg, both per 2500 m². This strategic approach to fertilization aims to optimize nutrient uptake during critical growth stages. The cultivation process commenced on November 23, 2023, utilizing mechanical ploughing techniques to prepare the soil adequately for planting. This method not only creates a uniform seedbed but also ensures the effective incorporation of fertilizers into the soil. The choice of cultivation practices and the timing of fertilizer applications are crucial for maximizing crop yield and quality in this region, which is characterized by unique environmental challenges. Overall, this study area provides a representative setting for examining the effects of various agronomic interventions on crop yield in the context of Iraq's agricultural landscape. The field of study focuses on a local wheat cultivar, BHOUTH 22, with an average seed sowing rate of 50 kg per 2500 m², implemented through mechanical methods. This structured plot allows for detailed observation and analysis of the crop yield across the designated sections, facilitating a comprehensive assessment of the cultivars' growth and productivity. The field area is organized into 4 transects, with each transect measuring 625 m², the experimental field utilizes fixed sprinkler irrigation, equipped with a total of 24 sprinklers. To ensure even distribution of irrigation water, the sprinklers are spaced 12 meters apart in width and 18 meters apart in length, as illustrated in Figure 1. Irrigation was carried out systematically every 3 days and every 6 days to evaluate the differences among the various treatments in order to analyze the changes in chlorophyll levels and crop yield.

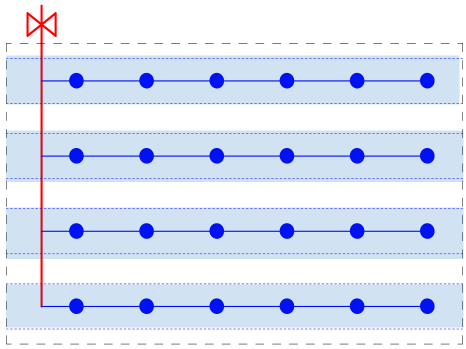

Fig 1. Layout of Experimental Field for Wheat Cultivar BHOUTH 22 and Irrigation System Design.

Measuring Soil Properties

Measuring soil properties is essential for effective soil management and ensuring optimal growth conditions for plants. To determine soil pH, a pH meter or test kit can be used by mixing a soil sample with distilled water in a 1:1 ratio. Electrical conductivity (ECe) is measured similarly, using the same soil-to-water ratio and an EC meter (Hendershot & Duquette, 1986). Total carbonate content can be assessed through an acid digestion method, where hydrochloric acid is added to the soil until effervescence stops (Nelson & Sommers 1982). Cation exchange capacity (CEC) is determined by saturating the soil with ammonium acetate and measuring the displaced cations (Thomas 1982). Organic matter content is evaluated using the loss on ignition method, where a soil sample is ignited at 360°C and weight loss is calculated (Walkley & Black1934). Chloride levels can be assessed using potentiometric titration with silver nitrate, while bicarbonate is measured through titration with a standard acid solution. For carbonate measurement, the acid digestion method is again employed. Magnesium and potassium are extracted using ammonium acetate, with magnesium analyzed through atomic absorption spectroscopy (AAS) and potassium measured using flame photometry or AAS. Nitrogen content is determined using either the Kjeldahl method or combustion method, while phosphorus is extracted using Bray or Olsen solutions and quantified through colorimetric analysis. Iron and zinc are extracted using DTPA and analyzed through AAS. Calcium is measured similarly to magnesium, and soil texture can be assessed using the hydrometer method or the feel method, which involves measuring sedimentation rates of different particle sizes (Soil & Plant Analysis Council, 2000).

Statistical Analysis

The collected data were analyzed using a two-way analysis of variance (ANOVA) with SPSS software (version 24). Significance between treatments was assessed using Student's t-test. The relationships among variables were evaluated through Pearson's correlation test.

Results and Discussion

Soil properties overview

The table 1 summarizes key soil properties, which are crucial for understanding soil health and fertility.

The soil properties indicate a moderately fertile environment that is well-suited for a variety of crops. The pH level of 7.61 suggests that the soil is slightly alkaline, which can significantly influence nutrient availability and microbial activity in the soil ecosystem. Alkaline soils can enhance the availability of certain nutrients, such as calcium and magnesium, while potentially limiting others, like iron and manganese, which are crucial for plant health. Therefore, monitoring pH levels is essential to ensure that all necessary nutrients remain accessible to plants (Msimbira & Smith, 2020). The electrical conductivity (ECe) is 2.50 dS/m. While some salinity can be beneficial, excessive levels may hinder plant growth by affecting water uptake and nutrient absorption. Plants may struggle to thrive in saline conditions, leading to reduced yields and compromised health. Proper irrigation practices and soil amendments are essential for managing salinity and maintaining a conducive growing environment.(Mannan et al., 2024). A total carbonate content of 120.00 g/kg may influence the soil's pH and overall chemistry. High carbonate levels can contribute to alkalinity, impacting the solubility of nutrients and thereby affecting plant growth. Understanding the carbonate dynamics is essential for managing soil fertility and ensuring that plants receive the required nutrients in optimal proportions (Bolan et al., 2023). The cation exchange capacity (CEC)

Table 1. physicochemical properties of the soil of study area's soil

Property	Value	Unit of Measurement
Soil pH	7.61	-
Electrical Conductivity (ECe)	2.50	dS/m
Total Carbonate Content	120.00	g/kg
Cation Exchange Capacity (CEC)	8.48	cmol/kg
Organic Matter	5.38	g/kg
Chloride (Cl)	10	mmol/l
Bicarbonate (HCO_3)	1.8	mmol/l
Carbonate (CO_3)	0	mmol/l
Magnesium (Mg)	3.1	mg/kg
Potassium (K)	52.10	mg/kg
Nitrogen (N)	0.35	mg/kg
Phosphorus (P)	114.35	mg/kg
Iron (Fe)	17.5	mg/kg
Zinc (Zn)	17.55	mg/kg
Calcium (Ca)	7.3	mmol/l
Soil Texture	Sandy loam	-

of 8.48 cmol/kg demonstrates the soil's ability to retain and exchange positively charged ions (cations), which are vital for nutrient availability. A moderate CEC indicates a reasonable capacity for holding essential nutrients such as potassium, calcium, and magnesium, making them available to plants. Enhancing CEC through organic matter addition can further improve nutrient retention and soil fertility (Adeyemo et al., 2023). The organic matter content of 5.38 g/kg is crucial for enhancing soil fertility and structure. Organic matter ameliorates water retention, increases microbial activity, and enhances nutrient cycling, all of which contribute to healthier plant growth. Additionally, organic matter plays a key role in soil aggregation, which improves soil aeration and drainage, further benefiting root development (Cotrufo & Lavallee 2022). The soil is classified as sandy loam, comprising 830 g/kg sand, 36 g/kg silt, and 134 g/kg clay. This texture provides an excellent balance between drainage and moisture retention, making it ideal for many agricultural practices. Sandy loam soils typically warm up quickly in the spring, allowing for earlier planting, while also retaining sufficient moisture during dry periods. This texture supports root penetration and facilitates healthy plant growth. Nutrient levels in the soil are also noteworthy. The presence of chloride (10 mmol/l) and bicarbonate (1.8 mmol/l) indicates specific ions that can affect soil chemistry and plant health. Adequate levels of essential nutrients include magnesium (3.1 mg/kg), potassium (52.10 mg/kg), nitrogen (0.35 mg/kg), phosphorus (114.35 mg/kg), iron (17.5 mg/kg), and zinc (17.55 mg/kg). These nutrients are critical for various physiological functions in plants. For instance, phosphorus plays a critical role in energy transfer and root development, while potassium regulates water uptake and enzyme activation. The presence of these nutrients suggests a favorable condition for plant growth, particularly with the sufficient phosphorus and potassium levels that support healthy development and high yields. Lastly, the calcium level at 7.3 mmol/l is important for maintaining cell wall structure and overall plant vitality. Calcium plays a crucial role in cell division and growth, and it helps in the formation of root systems, enhancing the plant's ability to absorb water and nutrients (Kisekka, 2024). The overall assessment of these soil properties indicates a healthy and fertile environment conducive to crop growth. However, it is essential to continuously monitor and manage factors such as salinity and pH to maintain optimal soil conditions. Implementing sustainable agricultural practices, such as crop rotation, cover cropping, and organic amendments, can further enhance soil health and productivity, ensuring long-term agricultural sustainability.

Yield Comparison of BUHOTH 22 Cultivar under Different Irrigation Intervals

The yield data collected at the end of April for the BUHOTH 22 cultivar reveals that the yield for the 6-day irrigation interval was 552 g/m², resulting in a total of 1380 kg for 2500 m². In contrast, the yield for the 3-day irrigation interval was slightly lower at 485 g/m², equating to 1212.5 kg for the same area. However, it is important to note that the differences in yield between the two irrigation schedules were not statistically significant at the 5% level. While 6 days' interval irrigations showed superiority under water stress condition. This suggests that both irrigation strategies can be effectively utilized without substantial impact on the overall yield of the BUHOTH 22 cultivar, providing flexibility for farmers in managing water resources (Alghawry et al., 2021).

Study of Chlorophyll Fluorometers

In this study, we investigated the effects of a fixed irrigation system combined with deficit irrigation technique on the physiological responses of wheat crop during its developing stage. Irrigation was scheduled every 3-days, with a specific deficit irrigation approach applied over two 6-day transects. This methodology allowed us to closely monitor crop health and plant responses under varying conditions.

To assess the health and photosynthetic activity of the plants, we utilized chlorophyll fluorometers, specifically the Junior-PAM, across 2 treatments. This instrument measures the fluorescence emitted by chlorophyll, providing valuable insights into the plant's overall condition and its ability to convert light energy into chemical energy (Tables 2 and 3); (Tolimir et al., 2024).

Relative Electron Transport Rate (ETR)

The relative electron transport rate (ETR) was calculated using the formula (Masojídek et al., 2001):

This equation highlights the importance of the effective photochemical quantum yield

$$ETR=PAR\times ETR\text{-}Factor\times PpsII/Ppps\times Y(II)ETR=PAR\times ETR\text{-}Factor\times PpsII/Ppps\times Y(II) \quad (1)$$

of Photosystem II (PS II), denoted as Y(II). The ETR is influenced by the photon flux density (PAR) absorbed by PS II, which is critical for understanding the efficiency of photosynthesis. PpsII/Ppps means photon absorbed by PSII relative to photons absorbed by photosynthetic pigments.

PAR Considerations

For accurate ETR calculations, we relied on the PAR values provided by the Junior-PAM's internal settings, specifically calibrated for a 400 mm fiber at a distance of 1 mm from the sample. It is important to note that variations in illumination conditions can affect the PAR values used in the ETR calculations. Additionally, long-term use or potential defects in the light fiber may lead to decreased LED output, impacting the photosynthetic photon flux density (PPFD) delivered by the Junior-PAM (Schansker, 2020) (Tables 2 and 3).

Fluorescence Quotients

To further quantify the photochemical and non-photochemical losses of absorbed light energy, we derived fluorescence quotients from relative fluorescence yield measurements. These quotients include Fv/Fm and Y(II), which estimate the fraction of absorbed quanta utilized for PS II photochemistry (Schansker, 2020) (Tables 2 and 3).

Physiological Status of Local Cultivars

The physiological status of the local cultivar, BUHOTH 22, was assessed through the aforementioned measurements. The results provide insights into how these cultivars respond to different irrigation strategies and their overall photosynthetic efficiency, contributing to our understanding of their adaptability and health in varying environmental conditions (Tables 2 and 3). The findings indicate that the wheat cultivar subjected to water stress exhibited slight differences compared to those not exposed to such conditions, with cultivars adapted to desert environments demonstrating notable resilience to extreme conditions and limited water availability (Morsy et al., 2022). During the 6-day water stress exposure, the cultivar maintained a higher rate of photosynthetic activity and overall growth metrics, showcasing its superior adaptation to drought. Remarkably, local variety, including BUHOTH

Table 2. BUHOTH 22 cultivar /3-days irrigation period interval, [WinControl (rev1219)]

No.	1:F	1:Fm'	1:PAR	1:Temp	1:Y (II)	1:ETR	1:Fo'	1:ETR-F.	1:qP	1:qN	1:qL	1:NPQ	1:Y (NO)	1:Y (NPQ)	1:Fo	1:Fm	1:Fv/Fm
1	126	429	0	37.2	0.706	0	0	0.84	0	0	0	0	0	0	126	429	0.706
2	171	368	125	36	0.535	28.1	120	0.84	0.794	0.182	0.557	0.166	0.399	0.066	126	429	0.706

Table 3. BUHOTH 22 cultivar /6-days irrigation period interval, [WinControl (rev1219)]

No.	1:F	1:Fm'	1:PAR	1:Temp	1:Y (II)	1:ETR	1:Fo'	1:ETR-F.	1:qP	1:qN	1:qL	1:NPQ	1:Y (NO)	1:Y (NPQ)	1:Fo	1:Fm	1:Fv/Fm
1	12	464	0	34.3	0.672	0	0	0.84	0	0	0	0	0	0	152	464	0.672
2	149	367	125	35.5	0.594	31.2	140	0.84	0.96	0.272	0.902	0.264	0.321	0.085	152	464	0.672

22, experienced only a minimal yield reduction of less than five percent ($P_{Value} \leq 0.05$) allowing them to remain productive under stress. Furthermore, implementing water conservation strategies, such as deficit irrigation, yielded positive results, enhancing physiological activity and optimizing water use in these cultivars (Wang, et al., 2023). These findings underscore the potential of BUHOTH 22 for sustainable agriculture in arid regions, as their resilience can ensure food security and economic viability.

Conclusion

This study is concerned with the remarkable resilience of the BUHOTH 22 wheat cultivar during water scarcity conditions. It is evident that photosynthesis can still occur even under extreme water shortages resulting in minimal yield loss.. Adaptive soil properties combined with proper irrigation techniques significantly enhance water use efficiency. Physiological function is improved with deficit irrigation which, together with greater water use efficiency, promotes sustainable agricultural practices. This is crucial to food security in drought-prone regions, which is why the results of this study are very significant. Greater insights into these processes will improve the management of soil health, which, in turn, will lead to higher yields and more resilient agricultural systems. . Along with preserving the needed conditions for agriculture in this increasingly challenging climate, these findings highlight the necessity of integrating cultivars like BUHOTH 22 on a wide, if not global, scale for agricultural sustainability. So, to further augment crop production and water conservation, these drought tolerant varieties should be adopted but with scrutiny for implications in the seasons to come and the genetics behind them.

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References:

Adeyemo, A. J., Ayorinde, A. S., Awodun, M. A., & Oyun, M. B. (2023). Nutrients status and soil microbial biomass C and N in charcoal production sites of derived savannah forest of southwestern Nigeria. *Scientific African*, *20*, e01684. https://doi.org/10.1016/j.sciaf.2023.e01684

Ahmed, K., Shabbir, G., Ahmed, M., & Shah, K. N. (2020). Phenotyping for drought resistance in bread wheat using physiological and biochemical traits. *Science of the Total Environment*, *729*, 139082. https://doi.org/10.1016/j.scitotenv.2020.139082

Alghawry, A., Yazar, A., Unlu, M., Çolak, Y. B., Iqbal, M. A., Barutcular, C., et al.. (2021). Irrigation rationalization boosts wheat (Triticum aestivum L.) yield and reduces rust incidence under arid conditions. *BioMed Research International*. https://doi.org/10.1155/2021/5535399

Bartold, M., & Kluczek, M. (2024). Estimating of chlorophyll fluorescence parameter Fv/Fm for plant stress detection at peat lands under Ramsar Convention with Sentinel-2 satellite imagery. *Ecological Informatics*, *81*, 102603. https://doi.org/10.1016/j.ecoinf.2024.102603

Bolan, N., Srivastava, P., Rao, C. S., Satyanaraya, P. V., Anderson, G. C., Bolan, S., ... & Kirkham, M. B. (2023). Distribution, characteristics and management of calcareous soils. *Advances in agronomy*, *182*, 81-130. https://doi.org/10.1016/bs.agron.2023.06.002

Cotrufo, M. F., & Lavallee, J. M. (2022). Soil organic matter formation, persistence, and functioning: A synthesis of current understanding to inform its conservation and regeneration. *Advances in agronomy*, *172*, 1-66. https://doi.org/10.1016/bs.agron.2021.11.002

Hu, F., Zhang, Y., & Guo, J. (2023). Effects of drought stress on photosynthetic physiological characteristics, leaf microstructure, and related gene expression of yellow horn. *Plant Signaling & Behavior*, *18*(1), 2215025. https://doi.org/10.1080/15592324.2023.2215025

Huang, J., Wang, S., Guo, Y., Chen, J., Yao, Y., Chen, D., ... & Xiang, Y. (2024). Hysteresis between winter wheat canopy temperature and atmospheric temperature and its driving factors. *Plant and Soil*, *499*(1), 55-71. https://doi.org/10.1007/s11104-022-05509-y

Khalid, A., Hameed, A., & Tahir, M. F. (2023). Wheat quality: A review on chemical composition, nutritional attributes, grain anatomy, types, classification, and function of seed storage proteins in bread making quality. *Frontiers in Nutrition*, *10*, 1053196. https://doi.org/10.3389/fnut.2023.1053196

Kisekka, I. (2024). Assessing the state of knowledge and impacts of recycled water irrigation on agricultural. *Crops and Soils*. 4964, https://doi.org/10.34951/E2WC7K

Mannan, M. A., Karim, M. A., Higichi, H., Akter, M., & Akter, M. T. (2024). Soil Management and Crop Adaptation in Saline Areas. In *Climate Change and Soil-Water-Plant Nexus: Agriculture and Environment* (pp. 397-431). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-97-6635-2_13

Masojídek, J., Grobbelaar, J. U., Pechar, L., & KoblíŽek, M. (2001). Photosystem II electron transport rates and oxygen production in natural waterblooms of freshwater cyanobacteria during a diel cycle. *Journal of Plankton Research*, 23(1), 57-66. https://doi.org/10.1093/plankt/23.1.57

Morsy, S. M., Elbasyoni, I. S., Abdallah, A. M., & Baenziger, P. S. (2022). Imposing water deficit on modern and wild wheat collections to identify drought-resilient genotypes. *Journal of Agronomy and Crop Science*, 208(4), 427-440. https://doi.org/10.1111/jac.12493

Msimbira, L. A., & Smith, D. L. (2020). The roles of plant growth promoting microbes in enhancing plant tolerance to acidity and alkalinity stresses. *Frontiers in Sustainable Food Systems*, *4*, 106. https://doi.org/10.3389/fsufs.2020.00106

Nabhan, G. P., Riordan, E. C., Monti, L., Rea, A. M., Wilder, B. T., Ezcurra, E. & Hodgson, W. C. (2020). An Aridamerican model for agriculture in a hotter, water scarce world. *Plants, People, Planet*, *2*(6), 627-639. https://doi.org/10.1002/ppp3.10129

Schansker, G. (2020). Chlorophyll Fluorescence and Photosynthesis: Simple Experiments with the JUNIOR-PAM Chlorophyll Fluorometer. *Heinz Walz GmbH*.

Soil, & Plant Analysis Council. (2000). Soil analysis handbook of reference methods. CRC Press. https://doi.org/10.1201/9780203739433

Tolimir, M., Gajić, B., Kresović, B., Životić, L., Gajić, K., Brankov, M., & Todorovic, M. (2024). Impact of deficit irrigation and planting density on grain yield and water productivity of maize grown under temperate continental climatic conditions. *Agricultural Water Management*, *302*, 109009. https://doi.org/10.1016/j.agwat.2024.109009

Wang, X., Ge, J., He, M., Li, Q., Cai, J., Zhou, Q. & Jiang, D. (2023). Enhancing crop resilience: Understanding the role of drought priming in wheat stress response. *Field Crops Research*, *302*, 109083. https://doi.org/10.1016/j.fcr.2023.109083

Wang, Y., Liu, S., & Shi, H. (2023). Comparison of climate change impacts on the growth of C3 and C4 crops in China. *Ecological Informatics*, *74*, 101968. https://doi.org/10.1016/j.ecoinf.2022.101968

Yadav, A., Upreti, H., & Singhal, G. D. (2024). Crop water stress index and yield relationships for winter wheat (Triticum aestivum) crops grown under different drip and flood irrigated treatments. *Journal of Agronomy and Crop Science*, *210*(6), e12775. https://doi.org/10.1111/jac.12775

Yanagi, M. (2024). Climate change impacts on wheat production: Reviewing challenges and adaptation strategies. *Advances in Resources Research*, *4*(1), 89-107. https://doi.org/10.50908/arr.4.1_89

Yu, L., Zhao, X., Gao, X., Jia, R., Yang, M., Yang, X. & Siddique, K. H. (2021). Effect of natural factors and management practices on agricultural water use efficiency under drought: A meta-analysis of global drylands. *Journal of Hydrology*, *594*, 125977. https://doi.org/10.1016/j.jhydrol.2021.125977

Zia, R., Nawaz, M. S., Siddique, M. J., Hakim, S., & Imran, A. (2021). Plant survival under drought stress: Implications, adaptive responses, and integrated rhizosphere management strategy for stress mitigation. *Microbiological research*, *242*, 126626. https://doi.org/10.1016/j.micres.2020.126626

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The role of potassium and Zinc Fertilizer and Irrigation period in wheat production in Basrah, Iraq

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Abstract

It is estimated that by 2050, food production should increase by 70% to sustain a global population of 9.1 billion people. This research examines the setting interactions of potassium (K, 80+16kg/ha) and Zinc (Zn, 1kg/ha) and Irrigation period in wheat (*Triticum aestivum L.*) in Basrah, Iraq, where salt concentration in soil severely limits agricultural productivity. The experiment was carried out in sandy loam soil of moderate salinity employing a randomized complete block design (RCBD) with the wheat subjected to Irrigation period treatments for 3 and 6-day intervals. The data indicates that both K and Zn individually and in combination considerably increased the height and yield of plants above the control. In other words, the control treatment resulted from drastic reductions in growth and yield over time. Nutrient management is essential. Strict salt management and the application of Zn and K increased the growth of wheat significantly more than did saline irrigation without Zn and K. These results highlight the importance of integrated nutrient management in increasing wheat productivity and resilience in regions with high salinity problems to help foster sustainable agriculture with rising environmental burden.

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Introduction

The global population is projected to increase by 34% by 2050, reaching around 9.1 billion, necessitating a 70% rise in food production (FAO, 2005). Modern agriculture faces multiple abiotic stresses, notably salinity, which significantly hampers crop yields by disrupting metabolic processes and causing irreparable damage (Tardieu & Tuberosa, 2010). In Pakistan, about 70% of agricultural soils are zinc deficient, exacerbating potassium deficiencies (Abbas et al., 2009). Zinc is crucial for reducing sodium accumulation and enhancing potassium uptake during salinity stress (Jan et al., 2017). To combat oxidative damage from reactive oxygen species, plants rely on robust antioxidant systems. Improving the availability of potassium and zinc can enhance the salinity tolerance of wheat (*Triticum aestivum L.*), ultimately contributing to agricultural resilience and food security (Hasanuzzaman et al., 2020).

The relationship between potassium (K), zinc (Zn), and salinity stress plays a critical role in determining the resilience of wheat (*Triticum aestivum L.*) under challenging environmental conditions. Wheat plants encounter significant hurdles when subjected to saline environments, largely due to osmotic pressure and ionic imbalances that inhibit water absorption and lead to the accumulation of toxic ions (Jan et al., 2017). These detrimental conditions increase oxidative stress within the plant system, severely compromising growth and development. To protect against cellular damage, wheat relies on osmolytes to stabilize macromolecules and detoxify harmful ions (Bouremani et al., 2023).

Potassium is integral to numerous physiological processes within plants, including photosynthesis, enzyme activation, and the movement of nutrients. However, salinity often drastically reduces the availability of potassium, which can hinder the growth and overall health of plants. Research indicates that maintaining appropriate potassium levels within plant cells is essential for combating oxidative stress induced by salt, preventing subsequent cellular damage. Adequate potassium not only enhances the functionality of antioxidant enzymes but also contributes to the resilience of plants facing salinity stress, underlining its importance for wheat cultivation in saline regions. Studies have shown that potassium helps regulate the K^+/Na^+ ratio, thereby improving the plant's ability to manage sodium toxicity and maintain osmotic balance (Xu et al., 2020; Wang et al., 2013).

Zinc serves as a crucial micronutrient that supports plant development and plays a significant role in stress management under saline conditions. As a cofactor for various enzymes essential for regulating stress responses, zinc helps protect plants against oxidative damage. Furthermore, zinc stabilizes cellular structures and regulates gene expression and protein synthesis, crucial for maintaining cellular integrity (Molnár et al., 2022). Adequate levels of zinc are necessary to fortify plants against oxidative stress, making it an indispensable component of nutrient management strategies in agriculture. The synergistic application of potassium and zinc can provide significant benefits to wheat varieties under salinity stress (Gupta et al., 2024).

Together, these nutrients enhance growth characteristics while alleviating stress, promoting better physiological responses in wheat plants. For instance, the application of both K and Zn has been shown to improve photosynthetic efficiency, boost antioxidant enzyme activities, and increase overall physiological performance. This relationship underscores the necessity of integrated nutrition management that incorporates both potassium and zinc to improve resilience and yield potential in wheat cultivated in saline environments (Bashir et al., 2023). The interplay between potassium and zinc is vital for mitigating the adverse impacts of salinity stress in wheat. Both nutrients are essential for maintaining cellular homeostasis and function, thereby supporting growth and development under stressful conditions. Effective management of these nutrients can lead to improved wheat performance, offering promising strategies for enhancing agricultural productivity in saline-affected regions (Choudhary et al., 2024). By ensuring adequate nutritional supply, farmers and agronomists can promote wheat resilience and sustain yield in the face of increasing salinity challenges.

The issue of soil salinity in Basrah, Iraq, is a significant environmental challenge that adversely affects agricultural productivity and necessitates comprehensive research and management strategies. The following detailed information outlines the extent of salinity, its causes, and its impact on agriculture in the region. Soil salinity has been a growing concern in Basrah, where increased salinization has rendered substantial areas of agricultural land less productive. In the last 13 years, salinized land has expanded by approximately 6,579.1 km², and in 2003, 34.5% of the total agricultural area was affected by salinity. By evaluating historical data from remote sensing and geographic information systems (GIS), researchers have documented that the situation continues to deteriorate, primarily due to the rising salinity levels in groundwater and soil (Jabbar & Zhou, 2012; Abdulameer et al., 2021).

The necessity of research into the relationship between potassium (K), zinc (Zn), and salinity stress in wheat (*Triticum aestivum L.*) is emphasized by the increasing challenges that modern agriculture faces due to the rising incidence of soil salinity, which directly threatens global food security. The anticipated growth in the global population necessitates that wheat production not only meets current demands but also adapts to the adverse effects of salinity that can significantly compromise crop yields. In light of the complexities surrounding salinity stress faced by wheat crops, the strategic application of potassium and zinc can greatly improve yield and crop quality. The aim of the research project in Basrah, Iraq, is to investigate the interactive effects of potassium (K) and zinc (Zn) on the salinity tolerance of wheat (*Triticum aestivum L.*) under local saline conditions.

Materials and Methods

Study Area

The research was conducted in Al_Zubair/Alluhais location, a city located in the Basrah province of Iraq. The specific study site encompasses an area of 0.25 hectares (2500 m²) with geographical coordinates of 30°34'08"N latitude and 46°58'14"E longitude.

Soil Characteristics

The soil type in the study area is sandy loam, which is characterized by a balanced mixture of sand, silt, and clay, providing good drainage and aeration. The soil properties of the study area were assessed to evaluate their suitability for agricultural practices. The electrical conductivity of the soil (Ecs) was measured at 4.5 dS/m, indicating moderate salinity levels, while the electrical conductivity of the soil extract

(Ece) was significantly higher at 9.1 dS/m, suggesting elevated salinity that could potentially impact crop growth negatively. Additionally, the soil pH was recorded at 7.61, reflecting neutral to slightly alkaline conditions, which are generally favorable for most crops. To enhance soil fertility, 5000 kg/ha of organic matter, sourced from cow manure, was applied to the plot on November 1, 2023. This organic amendment aims to improve soil structure and nutrient availability, thereby supporting healthy crop development.

Irrigation water characterization

Water for agriculture is sourced from groundwater via wells. This strategy provides famers with a dependable and constant water supply, especially in regions with little rainfall. Groundwater utilization has the potential to improve agricultural yields, but concerns regarding the over-usage and pollution of groundwater resources must be addressed with especial attention to water resource management. Moreover, the quality of the marketed water must be tested so that it meets the irrigation requirement and is not detrimental to the soil and plants. As shown in Table 1, irrigation water which has slightly alkaline pH value, with low electrical conductivity is noticeably cheaper and is also of suitable quality to be used for irrigation. Nevertheless, total hardness together with the elevated sodium concentration may hinder plant growth together with the infiltration of water into soil. Additionally, the elevated concentrations of calcium and magnesium may be referred to as hard water. Nitrate and potassium levels are fairly okay, but chloride and sulfate levels ought to be watched closely and lowered. As well, soil and plant damage from low amounts of heavy metals like cadmium, lead, nickel, and selenium should be avoided.

Fertilization and crop management

A comprehensive fertilization regime was implemented to support the growth of the crops in the study area. On November 23, 2023, during the mechanical sowing of wheat, 25 kg of DAP (Diammonium Phosphate)/donum was applied per

Table 1. Chemical and physical properties of irrigated water

Parameters	Unit	Irrigated water
pH	-	7.11
EC	µS/m	9.1
T.H	mg/L	2250
Ca^{+2}	mg/L	500
Mg^{+2}	mg/L	409.9
Na^{+}	mg/L	680
K^{+}	mg/L	40.5
Cl^{-}	mg/L	177.2
NO_3^{-}	mg/L	8
SO_4^{-2}	mg/L	795
Cd	mg/L	0.0214
Pb	mg/L	0.0153
Ni	mg/L	0.0441
CO	mg/L	0.0116

2500 m² to supply essential nutrients, particularly phosphorus, for early crop establishment. To address the nitrogen requirements of the wheat plants, urea fertilizer was applied in two doses on December 15, 2023. Totally, 65 kg urea/donum were applied, first dose 25 kg urea/donum at planting and the second dose (40 kg urea/donum). This strategic approach to fertilization aims to optimize nutrient availability and enhance crop performance throughout the growing season.

Cultivation practices

The cultivation process commenced on November 23, 2023, with mechanical ploughing employed to prepare the seedbed effectively. During this phase, two local wheat varieties, BHOUTH 22, were sown. An average seeding rate of 50 kg per 2500 m² was utilized to achieve optimal plant density, promoting healthy growth and development of the crops.

Experimental design

The study utilized a randomized complete block design (RCBD) to evaluate the performance of the two wheat varieties under the specified fertilization treatments. Each treatment was replicated to ensure statistical reliability. Data on crop growth parameters (e.g., plant height, biomass yield, grain yield) will be collected at regular intervals during the growing season.

The experimental field was systematically divided into 24 plots, with each plot measuring 80 m². The treatments included a control group and three fertilization regimes:The Potassium treatment (K, 80+16 kg/ha as K_2SO_4), total of 80+16 kg/ha was divided into two parts, the first part, 80kg/ha was applied at planting time, and second part 16 kg/ha was applied through sprinkler irrigation system on two months after planting. The zinc treatment (Zn, 1 kg/ha, as $ZnSO_4$) was applied through sprinkler irrigation system on two months after planting. The combination treatment of both of treatments (K+Zn), so that was explained earlier. The treatments of potassium and zinc were dissolved at a rate of 2.5 grams per liter water each and applied during irrigation system. The irrigation period was at intervals of 1 and 3 days. Each treatment has three replicated. The wheat variety used in the study was BHOUTH 22, and a fixed sprinkler irrigation system was employed to ensure uniform water distribution. additionally, the K fertilizer used in the farm soil and sprinkler irrigation. This methodical approach aimed to evaluate the effects of nutrient potassium and zinc supplementation on crop performance effectively.

Statistical analysis

Data will be subjected to statistical analysis using SPSS software (version 20) to evaluate the effects of different treatments on crop performance. ANOVA will be utilized to determine the significance of differences between treatments, with a significance level set at $p<0.05$.

Results and discussion

Soil properties

Soil tests conducted prior to cultivation revealed several key characteristics that inform the suitability of the soil for agricultural practices. The soil pH was measured at 7.61, indicating neutral to slightly alkaline conditions, which are generally favorable for crop growth. The electrical conductivity (ECe) was determined to be 4.5 dS/m, suggesting moderate salinity levels that may affect plant health. The total carbonate content was recorded at 12 g/kg, while the cation exchange capacity (CEC) was found to be 8.48 cmol/kg, indicating the soil's ability to retain essential nutrients. Organic matter content was measured at 6.9 g/kg, contributing to soil fertility and structure. The soil texture was classified as loamy sand, with sand, silt, and clay fractions comprising 830 g/kg, 36 g/kg, and 134 g/kg, respectively. Nutrient analysis showed adequate levels of magnesium (3.1 mg/kg), potassium (52.10 mg/kg), and phosphorus (14.1 mg/kg), while nitrogen content was relatively low at 0.35 mg/kg. Additionally, micronutrients such as iron (1.5 mg/kg) and zinc (1.2 mg/kg) were present in sufficient amounts. Overall, these soil properties indicate a moderate potential for successful crop cultivation, although attention to nutrient management will be necessary to optimize yields.

Effect of treatments on plant growth

Table 2 illustrates the effects of different treatments of potassium (K) and zinc (Zn) on the height of wheat over two irrigation intervals: 1 days and 3 days. At 1 days, the control group, which received no treatment, had an average height of 108.89 ± 20.99 cm. The application of potassium increased the height to 117.33 ± 10.44 cm, while zinc treatment resulted in a notable height of 126.33 ± 6.69 cm, indicating its significant positive impact. The combined treatment of K and Zn yielded a height of 119.44 ± 6.81 cm. However, at 6 days, the control group's height decreased to 86.11 ± 6.19 cm, suggesting a decline in growth without nutrient supplementation. In contrast, potassium treatment continued to support growth, reaching 121.11 ± 17.14 cm, while zinc slightly decreased to 119.78 ± 18.87 cm. The combined treatment of K and Zn proved most effective, achieving the highest average height of 126.44 ± 8.80 cm. Overall, the data emphasizes the importance of potassium and zinc in enhancing wheat growth, with the combined treatment yielding optimal results, highlighting the critical role of nutrient management in agriculture.

The results of the statistical analysis showed that there is a significant difference at the 1% level between 1 days and 6 days. This indicates that the growth patterns of wheat plants have varied significantly during this time frame. Additionally, in the treatments at 1 and 3 days, the results indicated that the treatment of zinc alone and the combination of zinc with potassium do not have a statistically significant difference, meaning that the significance level is above 5%. This means that neither zinc alone nor its combination with potassium leads to a notable increase in plant height. These findings suggest that while zinc is beneficial, its impact is not substantial enough to affect growth of height, whether alone or in combination

Table 2. Height (cm) of plant in the different treatment

	Treatment		Height
1 days	Control	0.0	108.89±20.99
	K	80+16 kg/ha	117.33±10.44
	Zn	1 kg/ha	126.33±6.69
	K and Zn	80+16 kg/ha + 1 kg/ha	119.44±6.81
3 days	Control	0.0	86.11±6.19
	K	80+16 kg/ha	121.11±17.14
	Zn	1 kg/ha	119.78±18.87
	K and Zn	80+16 kg/ha + 1 kg/ha	126.44±8.80

with potassium. In contrast, potassium has a more effective role in increasing plant height compared to zinc. On the other hand, the temporal changes observed between 1 and 3 days have a significant effect on plant growth, highlighting the importance of monitoring growth over time. Overall, these results emphasize the need for careful consideration of nutrient management strategies in agricultural practices to optimize plant growth and yield.

Effect of treatments on plant growth

Table 3 presents the weight of wheat (in tons per hectare) under different treatments of potassium (K) and zinc (Zn) over two time periods: 1 days and 3 days. After 3 days, the control group yielded 2.63 tons/ha, while treatments with potassium and zinc significantly increased yields to 4.09 tons/ha and 4.87 tons/ha, respectively. The combination of both nutrients resulted in the highest yield of 5.65 tons/ha. However, by 3 days, the control group's yield decreased to 2.33 tons/ha, indicating a lack of growth without treatment. The potassium and zinc treatments also saw declines, yielding 3.67 tons/ha and 3.83 tons/ha, respectively, while the combination treatment yielded 4.33 tons/ha. These results underscore the effectiveness of potassium and zinc in enhancing wheat yield, particularly when used together, but also highlight the need for ongoing nutrient management to maintain growth over time (Alharbi et al., 2024).

Statistical analysis showed that there is a significant difference at the 1% level between the results of the 1-day and 3-day fertilization treatments, indicating a substantial impact of time on plant growth. Additionally, only the control group (without fertilizer) showed a significant difference at the 1% level compared to other treatments, emphasizing the effectiveness of the applied fertilizers. In the 1-day period, the combination treatment of zinc and potassium exhibited a significant difference at the 1% level compared to the control group and other treatments, indicating the high efficiency of this combination in the early stages of growth. However, in comparison with other treatments, this combination did not show a significant difference, with a significance level exceeding 5%, suggesting that its advantage may not be sufficiently notable. These findings highlight the importance of timing and specific combinations of fertilizers in agricultural practices and indicate the need for ongoing monitoring and analysis to optimize fertilization strategies.

A noteworthy point is that the results of this study indicate the role of potassium

Table 3. Production (ton/ha) of plant in the different treatment

	Treatment		Production (ton/ha)
1days	Control	0.0	2.63±0.09
	K	80+16 kg/ha	4.09±0.09
	Zn	1 kg/ha	4.87±0.06
	K and Zn	80+16 kg/ha + 1 kg/ha	5.65±0.28
3days	Control	0.0	2.33±0.08
	K	80+16 kg/ha	3.67±0.08
	Zn	1 kg/ha	3.83±0.05
	K and Zn	80+16 kg/ha + 1 kg/ha	4.33±0.23

in increasing the height of wheat plants, while there was no significant difference in terms of yield. In other words, the applied potassium only has a more effective role in increasing height.

Potassium (K) and zinc (Zn) play distinct and essential roles in various physiological processes critical for plant growth and development. Potassium is a macronutrient associated with the movement of water, nutrients, and carbohydrates within plant tissues. It is involved in enzyme activation, which affects the production of protein, starch, and adenosine triphosphate (ATP), and it also regulates photosynthesis. Additionally, potassium is crucial for regulating the opening and closing of stomata, which controls the exchange of water vapor, oxygen, and carbon dioxide. Adequate potassium levels enhance root growth, improve drought resistance, maintain turgor, aid in food formation, reduce respiration, enhance sugar and starch translocation, increase protein content, build cellulose, and help retard crop diseases (Sardans & Peñuelas, 2021; Wang et al., 2013). Zinc, on the other hand, is a micronutrient and a key component of various enzymes that drive metabolic reactions in plants. It is essential for growth regulation through the formation of auxins and stem elongation (Umair Hassan et al., 2020). Zinc contributes to carbohydrate, protein, and chlorophyll formation and is necessary for starch formation and proper plant development. It also helps regulate photosynthesis by increasing photosynthetic pigments and soluble sugars, and it plays a role in seed and pollen grain regulation (Hamzah Saleem et al., 2022). Furthermore, zinc is involved in protecting plant cells from damage by reactive oxygen species, acting as a protective agent against oxidation. The simultaneous use of zinc and potassium fertilizers has positive effects on the growth and yield of wheat. These two elements synergistically enhance nutrient uptake, increase plant height, and improve grain quality. Potassium aids in better growth by activating enzymes and facilitating the movement of water and nutrients within the plant, while zinc, as an essential micronutrient, enhances the nutritional quality of grains and prevents yield reduction due to its deficiency (Jat et al., 2014; Bashir et al., 2023). Additionally, increased potassium levels can mitigate the negative effects of phosphorus on zinc uptake, thereby contributing to the overall quality and performance of wheat.

Conclusion

This study highlights the critical roles of potassium (K) and zinc (Zn) in enhancing both the height and yield of wheat plants over specified time intervals. The statistical analysis demonstrated significant differences in plant growth between the 1-day and 3-day treatments, emphasizing the importance of timely nutrient application. Notably, while potassium significantly increased plant height, its impact on yield was not as pronounced when compared to zinc, which showed a notable effect on yield but less influence on height. The combined treatment of K and Zn yielded the most favorable results, suggesting that the synergistic effects of these nutrients are crucial for optimizing wheat growth and production. However, the decline in growth and yield observed in the control group over time underscores the necessity of continuous nutrient management to sustain agricultural productivity. In conclusion, these findings advocate for the strategic integration of potassium and zinc in fertilization practices, tailored to the growth stages of wheat. Ongoing research and monitoring are essential to refine nutrient management strategies, thereby maximizing both the height and yield potential of wheat crops in agricultural systems.

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References

Abbas, G., Khan Q.M., Jamil M., Tahir M. & Hussain. F. (2009). Nutrient uptake, growth and yield of wheat (*Triticum aestivum L.*) as affected by zinc application rates. *International Journal of Agriculture and Biology*, 11, 389-396.

Abdulameer, A., Thabit, J. M., Kanoua, W., Wiche, O., & Merkel, B. (2021). Possible Sources of Salinity in the Upper Dibdibba Aquifer, Basrah, Iraq. *Water, 13*(4), 578. htps://doi.org/10.3390/w13040578

Alharbi, K., Alnusairi, G. S., Alnusaire, T. S., Alghanem, S. M., Alsudays, I. M., Alaklabi, A., & Soliman, M. H. (2024). Potassium silica nanostructure improved growth and nutrient uptake of sorghum plants subjected to drought stress. *Frontiers in Plant Science*, *15*, 1425834. https://doi.org/10.3389/fpls.2024.1425834

Bashir, A., Khan, Q. U., Alem, A., Hendi, A. A., Zaman, U., Khan, S. U., ... & Abdelrahman, E. A. (2023). Zinc and potassium fertilizer synergizes plant nutrient availability and affects growth, yield, and quality of wheat genotypes. *Plants*, 12(12), 2241. https://doi.org/10.3390/plants12122241.

Bouremani, N., Cherif-Silini, H., Silini, A., Bouket, A.C., Luptakova, L., Alenezi, F.N., Baranov, O. & Belbahri, L. (2023). Plant growth-promoting rhizobacteria (PGPR): A rampart against the adverse effects of drought stress. *Water*, *15*(3), 418. https://doi.org/10.3390/w15030418.

Choudhary, M., Garg, K., Reddy, M.B., Meena, B.L., Mondal, B., Tuti, M.D., Kumar, S., Awasthi, M.K., Giri, B.S., Kumar, S. & Rajawat, M.V.S. (2024). Unlocking growth potential: Synergistic potassium fertilization for enhanced yield, nutrient uptake, and energy fractions in Chinese cabbage. *Heliyon*, *10*(7). DOI: 10.1016/j.heliyon.2024.e28765.

FAO. (2005). Global network on integrated soil management for sustainable use of salt-affected soils. Rome, Italy: FAO Land and Plant Nutrition Management Service. http://www.fao.org/ag/AGL/agll/spush.

Gupta, A., Bharati, R., Kubes, J., Popelkova, D., Praus, L., Yang, X., Severova, L., Skalicky, M. & Brestic, M. (2024). Zinc oxide nanoparticles application alleviates salinity stress by modulating plant growth, biochemical attributes and nutrient homeostasis in Phaseolus vulgaris L. *Frontiers in Plant Science*, *15*, 1432258.https://doi.org/10.3389/fpls.2024.1432258.

Hamzah Saleem, M., Usman, K., Rizwan, M., Al Jabri, H., & Alsafran, M. (2022). Functions and strategies for enhancing zinc availability in plants for sustainable agriculture. *Frontiers in Plant Science*, 13, 1033092. https://doi.org/10.3389/fpls.2022.1033092.

Hasanuzzaman, M., Bhuyan, M.B., Zulfiqar, F., Raza, A., Mohsin, S.M., Mahmud, J.A., Fujita, M. & Fotopoulos, V. (2020). Reactive oxygen species and antioxidant defense in plants under abiotic stress: Revisiting the crucial role of a universal defense regulator. *Antioxidants*, *9*(8), 681. https://doi.org/10.3390/antiox9080681

Jabbar, M. T., & Zhou, J. (2012). Assessment of soil salinity risk on the agricultural area in Basrah Province, Iraq: Using remote sensing and GIS techniques. *Journal of Earth Science,* 23, 881-891. https://doi.org/10.1007/s12583-012-0299-5

Jan, A. U., Hadi, F., Nawaz, M. A., & Rahman, K. (2017). Potassium and zinc increase tolerance to salt stress in wheat (*Triticum aestivum L.*). *Plant Physiology and Biochemistry*, *116*, 139-149. https://doi.org/10.1016/j.plaphy.2017.05.008.

Jat, G., Majumdar, S. P., Jat, N. K., & Mazumdar, S. P. (2014). Effect of potassium and zinc fertilizer on crop yield, nutrient uptake and distribution of potassium and zinc fractions in Typic Ustipsamment. Indian *Journal of Agricultural Sciences*, 84(7), 832-8. https://doi.org/10.56093/ijas.v84i7.41994

Molnár, A., Kondak, S., Benkő, P., Janovszky, P., Kovács, K., Szőllősi, R., Gondor, O.K., Oláh, D., Gémes, K., Galbács, G. Janda, T, & Kolbert, Z. (2022). Limited Zn supply affects nutrient distribution, carbon metabolism and causes nitro-oxidative stress in sensitive Brassica napus. *Environmental and Experimental Botany*, *202*, 105032. https://doi.org/10.1016/j.envexpbot.2022.105032.

Sardans, J., & Peñuelas, J. (2021). Potassium control of plant functions: Ecological and agricultural implications. *Plants*, 10(2), 419. https://doi.org/10.3390/plants10020419

Tardieu, F. & R. Tuberosa. (2010). Dissection and modelling of abiotic stress tolerance in plants. *Current Opinion in Plant Biology,* 13, 206-212. https://doi.org/10.1016/j.pbi.2009.12.012.

Umair Hassan, M., Aamer, M., Umer Chattha, M., Haiying, T., Shahzad, B., Barbanti, L., Nawaz, M., Rasheed, A., Afzal, A., Liu, Y, & Guoqin, H. (2020). The critical role of zinc in plants facing the drought stress. *Agriculture*, 10(9), 396. https://doi.org/10.3390/agriculture10090396.

Wang, M., Zheng, Q., Shen, Q., & Guo, S. (2013). The critical role of potassium in plant stress response. *International journal of molecular sciences*, 14(4), 7370-7390. https://doi.org/10.3390/ijms14047370

Xu, X., Du, X., Wang, F., Sha, J., Chen, Q., Tian, G., Zhu, Z., Ge, S., & Jiang, Y. (2020). Effects of potassium levels on plant growth, accumulation and distribution of carbon, and nitrate metabolism in apple dwarf rootstock seedlings. *Frontiers in Plant Science,* 11. https://doi.org/10.3389/fpls.2020.00904

Original Article

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Using harvested rainwater from urban grass surfaces for landscapes irrigation: considering the effect of slope on run-off coefficient

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Abstract

Efficient water management is crucial in arid and semi-arid regions like Iran. In this study, the potential of rainwater harvesting (RWH) for irrigating urban parks and landscapes in Zanjan, Iran, was evaluated. For this purpose, the rainfall data from the Zanjan synoptic station during the period 2014-2022 was used. Using the ArcGIS software, the area and slope of parks and landscapes was determined. The volume of harvested rainwater from these surfaces was estimated using different run-off coefficients for different slopes. The results indicated that the total area of parks and landscapes in Zanjan is 537200 m², with slopes ranging from 0% to 18.47%. The irrigation requirements are only partially met by the harvested rainwater, except for March, when we had the most rain. In January and February, rainwater meets 7.68% and 12.60% of the needs, respectively. In March, all the water requirement is met, with extra water stored for April. This stored water fully meets the water requirement in April, with some left for May, covering 18.94% of its demand. In May, 26.88% of the needs are met. From June to December, rainwater meets between 0.54% and 10.92% of the needs. March, April and May have the highest potential for meeting irrigation needs through RWH. This emphasizes the importance of constructing RWH reservoirs, which helps save municipal water and prevents rainwater from being wasted.

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Introduction

Water scarcity stands as one of the most crucial challenges, highlighting the need to adopt innovative methods to meet the growing water demand, particularly in arid and semi-arid regions as well as developing countries. The limited rainfall in these regions has impacted natural resources and life, and the global climate change has intensified the challenges of water use (Yifru et al., 2021). Therefore, optimal use of water is always considered as a sustainable solution for the limited water resources (Wei et al., 2005; Kahinda et al., 2007; Helmreich & Horn, 2009).

Since rainfall occurs almost everywhere, harvesting, storing, and using rainwater as a supplementary technique for surface- and ground-water resources can supply part of the water required by various sectors and reduce urban floods. However, this supplementary resource is usually unavailable due to a lack of proper management (Opare, 2012; Rostami Khalaj et al., 2020; Beheshti et al., 2022; Chamani et al., 2022). The harvested and stored rainwater is less polluted than other water resources and can be used for drinking after disinfection (Vilane & Mwendera, 2011). According to the Pan American Health Organization (2017), even healthcare centers can use this water during times of crisis (PAHO, 2017). Accordingly, identifying the most suitable locations for rainwater harvesting (RWH) is a fundamental topic for global studies (Hatibu et al., 2006; Adham et al., 2016; Mahmoud et al., 2016).

Several studies have been conducted in the field of RWH for various uses. Gavit et al. (2018) used ArcGIS and remote sensing to investigate the sustainability of RWH structures in the Punad watershed, India, classifying the suitable locations into three categories based on the basin slope: high, medium, and low. Kanno et al (2021), using a 17-year dataset of rainfall, evaluated the potential of RWH in Dilla Town, Ethiopia, and stated that RWH can serve as an alternative resource for meeting domestic and industrial water requirements and even help supply water during the COVID-19 pandemic. Ahmed et al. (2022) studied RWH from rooftops at the Taxila University, Pakistan, and concluded that the monthly water which can be harvested from these surfaces equals 59% of available water resource for irrigation of trees and plants. Zhong et al. (2022) showed that RWH in Arizona can supply 32% of urban water requirements for eight months in a humid year, leading to an annual saving of $13.8 million. Jacque et al. (2023) investigated the hydrological feasibility of RWH for irrigation of landscapes and public gardens in the UK. They demonstrated that the gardens located in the more humid areas, with a low ratio of irrigation water demand to the amount water which can be harvested, have high potential for RWH. Halder and Bose (Halder & Bose, 2024) used remote sensing to identify and classify the suitable areas for RWH in Puralia, India. They compared the performance of Artificial Neural Network (ANN) and Random Forest (RF) in optimizing RWH strategies. Their findings revealed that rainfall, slope, run-off generation potential, soil, land cover, and drainage are the six key factors for selecting suitable locations for RWH. In Iran, Taran & Mahtabi (2016) assessed the potential of Bonab, Iran, for RWH. They concluded that by collecting run-off from all the urban surfaces in each month, 100% of the water demand of public, commercial and industrial centers can be supplied during the first two months of spring and from mid-fall to late-winter. Additionally, by collecting run-off from courtyards and rooftops in residential areas throughout the year, a portion of the domestic water demand could be met. Chamani et al. (2022) calculated the amount of water which can be harvested from annual rainfall in Aryan Shahr, Iran. They indicated that annually 141636 m^3 run-off can be harvested from the urban surfaces and utilized for various purposes, including irrigation of landscapes. Beheshti et al. (2022) investigated the use of retention ponds and rooftop rainwater collection in Birjand, Iran, and concluded that RWH can reduce run-off volume by 80% and contribute to landscape irrigation. Nevertheless, to our knowledge, the slope of urban surfaces from which rainwater is harvested and utilized for irrigation has not been taken into account so far in Iran. Slope is a key factor directly affecting the run-off coefficient and, consequently, the volume rainwater which can be harvested. In areas with steeper slopes, the volume of run-off increases due to reduced water infiltration into the soil (Park et al., 2014). The run-off coefficient is used to represent run-off generation on various regional scales and is defined as the ratio of the volume of surface water to the volume of rainfall over a specified period (Machado et al., 2022). Taking the factors affecting the run-off coefficient into consideration is particularly crucial in urban areas where there are many impervious surfaces and run-off is a serious threat (Shi et al., 2007). Despite the existence of standardized tables for run-off coefficients, recent studies have shown that these fixed values may not align with local realities and various environmental factors. For instance, Machado et al. (2022) indicated in their study in Sao Paulo, Brazil, that run-off coefficients calculated using hydrographs differed from the values found in standard tables and that the run-off coefficient had a strong correlation with land use. Similarly, Blume et al. (2007) emphasized that fixed run-off coefficients do not provide accurate information due to the influence of multiple environmental factors.

Among urban surfaces, according to the study by Mahtabi & Taran (2017), run-off generation on grass surfaces is more affected by slope than on other surfaces. In the present research, the potential for RWH from the grass surfaces in Zanjan, Iran, to supply irrigation water for the city's landscapes over the course of one year was examined. Irrigation of landscapes is important due to its numerous social benefits, including positive impacts on human physical and mental well-being (Maller et al., 2006; De Bell et al., 2020), contribution to tourism and labor economies (Croy et al., 2020), preservation of plant species diversity (Moyle & Weiler, 2017), and providing green infrastructure and ecosystem services (Cameron & Blanusa, 2016). For landscape irrigation, surface- and ground-water are often used, but these resources are especially limited during hot seasons and drought periods, requiring alternative resources. In this study, the total area of landscapes and grass surfaces in Zanjan, and their slopes in different parts of the city were determined. Then, the run-off coefficients for these surfaces in part were calculated. Finally, using monthly rainfall data, the run-off generated and, consequently, the potential amount of water which can be harvested from these surfaces were obtained. The innovative aspect of this study lies in its approach to incorporate the effect of slope on the run-off coefficient in RWH for urban grass surfaces in Iran. By highlighting the relation between slope variations and run-off generation, this study offers a more precise and localized method for estimating the potential of harvested rainwater. This focus addresses a critical gap in sustainable water management strategies, particularly in urban areas where impervious surfaces and water scarcity pose significant challenges.

Materials and Methods

Study Area

Zanjan city, the capital Zanjan province, is located at latitude 47° 47` N and longitude 37° 08`E and an elevation of 1663 m above sea level in northwest Iran. In 2025, the city's area is 65 km^2. According to the latest population and housing census, the city's population is reported to be approximately 52000 people. The location of Zanjan is shown in Figure 1.

Fig 1. The location of Zanjan in Iran

Rainfall

In this study, using data from the synoptic station of Zanjan, the 9-year (2014-2022) average of total monthly rainfall was obtained (Table 1).

Table 1. Nine-year monthly average of rainfall (mm)

Month	Rainfall	Month	Rainfall
January	36.16	July	5.86
February	53.60	August	2.52
March	79.73	September	5.98
April	62.19	October	42.64
May	37.37	November	49.79
June	7.11	December	44.22

The volume of harvested rainwater

The volume of harvested rainwater from a surface (run-off discharge) is calculated using Eq.1 (Taran & Mahtabi, 2016):

$$V=CIA \quad (1)$$

where, V (L) is the volume of harvested rainwater or the run-off quantity, I (mm) is the rainfall height, and A (m^2) is the rainwater harvesting area. C is the run-off coefficient of the surface and represents the portion of rainfall that can be converted into run-off.

The water requirement of parks and landscapes

According to Publication No. 117.3 of Design Criteria for Urban and Rural Water Transmission and Distribution Systems (2023), concerning water consumption in Iran up to 2018, this study determined the water requirements of the domestic and public landscapes in Zanjan. Based on the climate classification in this publication, Zanjan is located in two climatic regions: semi-arid and cold, and semi-humid and cold. The average daily water consumption for landscapes in these regions is estimated to be 1.5 to 2 $L.m^{-2}.day^{-1}$, with an average of 1.75 $L.m^{-2}.day^{-1}$.

Results and discussion

The area and slope of parks and landscapes

The area of parks and landscapes within the urban boundaries of Zanjan, along with the slope of each region, was obtained using the ArcGIS software. Table 2 presents the area corresponding to each slope class. The total area of the parks and landscapes was determined to be 537200 m^2. The minimum and maximum slope classes for parks and landscapes within the urban boundaries were 0-1.45% and 13.47-18.47%, respectively, with all slopes categorized between these two classes. The largest and smallest area were 145400 m^2 and 16900 m^2, respectively, belonging to 0-1.45% and 8.18-8.91% slope classes; these slope classes account for 27.06% and 3.14% of the total area of parks and landscapes, respectively. Figure 2 depicts the distribution of parks and landscapes within the urban boundaries of Zanjan.

Table 2. The areas and slopes of the parks and landscapes in the urban area

Slope class (%)	Average Slope (%)	Area ($m^2\times10^4$)	Percentage of area
0-1.45	0.72	14.54	27.06
1.45-2.10	1.77	4.00	7.45
2.10-3.91	3.00	2.53	4.71
3.91-5.14	4.52	2.74	5.10
5.14-6.01	5.57	2.11	3.92
6.01-6.88	6.44	1.90	3.53
6.88-7.46	7.17	2.11	3.92
7.46-8.18	7.82	2.11	3.92
8.18-8.91	8.54	1.69	3.14
8.91-9.56	9.23	2.53	4.71
9.56-10.28	9.92	2.53	4.71
10.28-11.23	10.75	3.58	6.67
11.23-12.10	11.66	2.74	5.10
12.10-13.47	12.78	4.42	8.24
13.47-18.47	15.97	4.21	7.84
Total	-	53.72	100

Fig 2. The distribution of parks and landscapes with different slopes withing the urban area

The run-off coefficients of parks and landscapes

According to the values of run-off coefficient for grass surfaces with the slopes of 5%, 10%, and 15%, reported as 0.09, 0.19, and 0.24, respectively, by Mahtabi & Taran (2017), the run-off coefficient for different slopes in the present study (Table 2) can be estimated by interpolation and using the trendline of the graph in Figure 3. It is noted that the quadratic equation provided the best trendline with R^2=0.97. Table 3 gives the values of run-off coefficient for parks and landscapes with different slopes.

The volume of run-off which can be harvested from parks and landscapes

Considering the values of monthly rainfall presented in Table 1 and using Eq.1, the volume of run-off generated on the park and landscape surfaces or rainwater which can be harvested from these surfaces withing the urban area of Zanjan in different months was calculated for various slopes, as given in Table 4. Since the lowest rainfall has occurred in August (2.52 mm), the smallest volume of

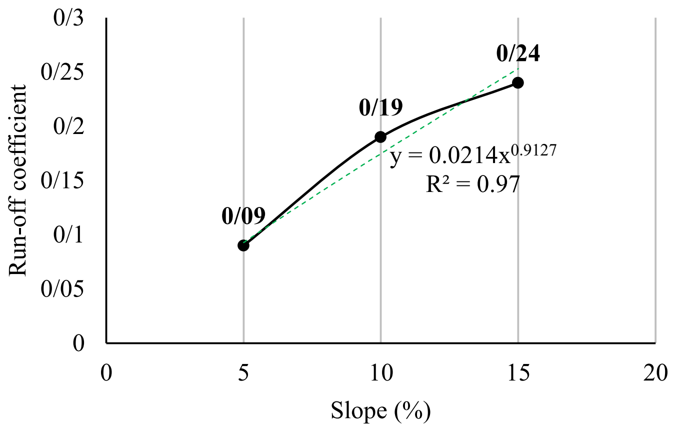

Fig 3. The trendline of the run-off coefficient of grass surfaces versus different slopes

Table 3. The estimated values of run-off coefficient for grass surfaces with different slopes

Average slope (%)	Run-off coefficient	Area ($m^2 \times 10^4$)
0.72	0.0159	14.54
1.77	0.0360	4.00
3.00	0.0583	2.53
4.52	0.0848	2.74
5.57	0.1026	2.11
6.44	0.1171	1.90
7.17	0.1292	2.11
7.82	0.1398	2.11
8.54	0.1515	1.69
9.23	0.1627	2.53
9.92	0.1738	2.53
10.75	0.1870	3.58
11.66	0.2014	2.74
12.78	0.2189	4.42
15.97	0.2683	4.21

rainwater which can be harvested belongs to this summer month (156058.97 L). in contrast, the largest volume of rainwater that can be harvested is 59019625.06 L which corresponds to the spring month of March with a rainfall of 79.73 mm.

Supplying the water required for the irrigation of parks and landscapes form the rainwater harvested from these surfaces

Since the water requirement of parks and landscapes in Zanjan is 1.75 $L.m^{-2}.day^{-1}$, and the total area of these surfaces is 537200 m^2, the water requirement was calculated in liters for each month (Table 5). It should be noted that the number of days in February, excluding leap years, was considered to be 28.

Figure 3 shows the volume of rainwater that can be harvested from parks and landscapes along with the water required for their irrigation in each month. The comparison between these two values reveals that in

Table 4. The volume of rainwater that can be harvested from parks and landscapes in different months

Run-off coefficient	V ($L\times10^3$)					
	January	February	March	April	May	June
0.0159	83.59	123.92	458.37	143.77	86.39	16.44
0.0360	52.06	77.18	1037.81	89.55	53.81	10.24
0.0583	53.33	79.06	1680.67	91.73	55.12	10.49
0.0848	84.01	124.54	2444.62	144.50	86.82	16.52
0.1026	78.27	116.04	2957.76	134.63	80.89	15.39
0.1171	80.44	119.25	3375.76	138.36	83.14	15.82
0.1292	98.56	146.12	3724.58	169.53	101.87	19.39
0.1398	106.65	158.11	4030.16	183.44	110.22	20.98
0.1515	92.57	137.23	4367.45	159.23	95.67	18.21
0.1627	148.83	220.63	4690.32	255.99	153.81	29.27
0.1738	158.98	235.69	5010.31	273.45	164.31	31.27
0.1870	242.05	358.83	5390.84	416.33	250.15	47.61
0.2014	199.52	295.78	5805.97	343.18	206.20	39.24
0.2189	349.82	518.60	6310.46	601.70	361.54	68.80
0.2683	408.39	605.44	7734.56	702.45	422.07	80.32
Total	2237.07	3316.42	59019.63	3847.85	2312.01	439.99

Run-off coefficient	V ($L\times10^3$)					
	July	August	September	October	November	December
0.0159	13.54	5.83	13.82	98.59	115.10	102.24
0.0360	8.43	3.63	8.61	61.41	71.70	63.68
0.0583	8.64	3.72	8.82	62.90	73.44	65.23
0.0848	13.61	5.86	13.89	99.09	115.69	102.75
0.1026	12.68	5.46	12.94	92.32	107.79	95.73
0.1171	13.03	5.61	13.30	94.88	110.78	98.39
0.1292	15.96	6.88	16.30	116.25	135.73	120.56
0.1398	17.27	7.44	17.63	125.79	146.87	130.45
0.1515	14.99	6.46	15.31	109.18	127.48	113.22
0.1627	24.10	10.38	24.61	175.54	204.95	182.03
0.1738	25.75	11.09	26.29	187.51	218.93	194.45
0.1870	39.20	16.89	40.02	285.49	333.32	296.05
0.2014	32.31	13.92	32.99	235.33	274.75	244.03
0.2189	56.65	24.40	57.84	412.60	481.73	427.87
0.2683	66.14	28.49	67.52	481.69	562.39	499.51
Total	362.30	156.06	369.87	2638.57	3080.62	2736.19

Table 5. The water requirements of parks and landscapes in different months ($L \times 10^3$)

Month	Water requirement	Month	Water requirement
January	29143.10	July	29143.10
February	26323.80	August	29143.10
March	29143.10	September	28203
April	28203	October	29143.10
May	29143.10	November	28203
June	28203	December	29143.10

all months, expect for March which has the highest amount of rainfall throughout the year, the harvested rainwater can only supply a portion of the water required for irrigating parks and landscapes. In January and February, 7.68% and 12.60% of the water requirement, respectively, are met through rainwater RWH. In march, in addition to meeting 100% of the water requirement, 29876.53 kL of the harvested rainwater can be stored for the following month (April). Burszta-Adamiak & Przybylska (2024), in their research in Poland, stated that water stored in above-ground tanks could be used for watering plants, covering 62 to 82% of the need. They implied that underground reservoirs, having more capacity, could meet the water demand completely. Given that the water requirement in April is 28,203 kL, the stored water can fully cover this requirement. However, since the harvested rainwater in April itself amounts to 3847.85 kL, a surplus of 5521.38 kL from the stored water in March remains available for use in May. This amount can supply 18.94% of the water requirement in May. Considering the rainwater harvested in May, which is 2312.01 kL, a total of 26.88% of the water requirement in May will be met. Using the harvested rainwater from June to December, respectively 1.56%, 1.24%, 0.54%, 1.31%, 9.05%, 10.92%, and 10.92% of the water required for irrigating parks and landscapes in Zanjan can be supplied. Therefore, throughout the year, in the three months of March, April, and May the highest percentage of irrigation water can be met through RWH. Since these three months coincide with spring in Iran, when the highest number of tourists visit cities across the country (Mahtabi & Taran, 2018), ensuring sufficient water reaches urban grass surfaces enhances the beauty of parks and landscapes. In general, using harvested rainwater can reduce irrigation expenses, making it a cost-effective option for maintaining public gardens and parks (Cauteruccio & Lanza, 2022; Jacque et al., 2023). Chiu et al. (2020) have stated that RWH can provide a substantial amount of water for irrigation, especially in arid regions like Iran, where traditional water resources are under stress. Also, Saeedi & Goodarzi (2020) have reported that RWH contributes to sustainable landscape development, helping to mitigate the effects of urbanization and climate change on water resources. These highlight the importance of constructing RWH reservoirs/tanks for irrigation of these surfaces, which not only contributes to saving municipal water but also prevents rainwater wastage (Rostami Khalaj et al., 2020; Wesseling et al., 2021). The importance of collecting and storing rainwater for irrigation use has been reported in several studies. For instance, Taran & Mahtabi (2016) found out that utilizing spring rainfall in Bonab, Iran, can not only meet the water demand of the landscapes during spring months, but also fully compensate for the water shortage during the first two months of summer. Wurthmann (2019) stated that if sufficiently stored, rainwater can supply the water required for irrigation of landscapes in Florida, USA.

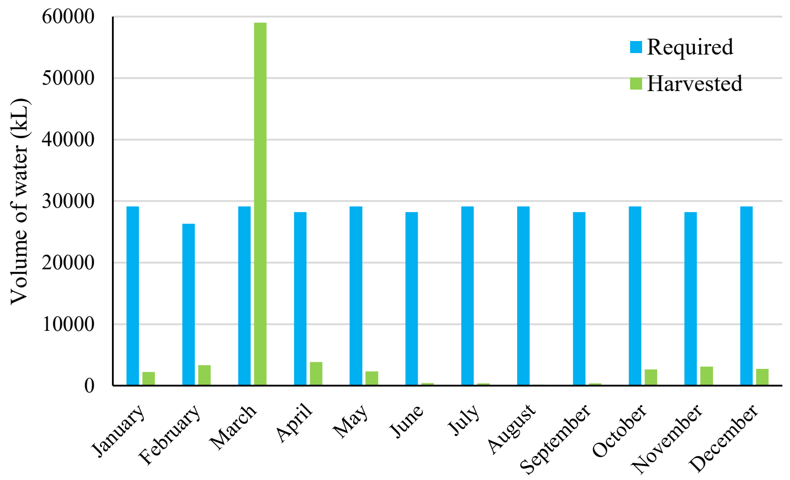

Fig 4. The volume of rainwater that can be harvested and the water required for irrigation

Conclusion

This research evaluated the potential of RWH for supplying irrigation water to parks and landscapes within the urban boundaries of Zanjan. The findings indicated that the total area of these surfaces is 537200 m², with varying slopes affecting run-off coefficients. Using rainfall data from a nine-year period (2014–2022), the volume of run-off generated in different months was calculated. The results showed that the highest volume of rainwater that can be harvested occurs in March, while the lowest occurs in August. The comparison between harvested rainwater and the monthly irrigation water requirement demonstrated that only March can fully meet the water requirement of parks and landscapes, with a surplus available for storage. The stored water from March can also fully meet the irrigation requirement in April and partially contribute to that of May. In contrast, during other months, RWH can only supply a fraction of the required irrigation water, ranging from 0.54% in September to 12.60% in February. Based on these findings, the construction of RWH reservoirs or storage tanks is recommended to save more water and minimize dependence on municipal water supplies. This is particularly important during spring, when tourism is at its highest, and keeping landscapes beautiful is essential for the city's appearance. Using RWH strategies can play a big role in sustainable water management by optimizing available water resources for irrigation purposes.

References

Adham, A., Riksen, M., Ouessar, M. & Ritsema, C. (2016). A methodology to assess and evaluate rainwater harvesting techniques in (semi-) arid regions. *Water*, 8 (5), 198. https://doi.org/10.3390/w8050198

Ahmed, A., Valyrakis, M., Ghumman, A.R., Arshad, M., Pasha, G.A., Farooq, R. & Janjua, S. (2022). Assessing the rainfall water harvesting potential using geographical information systems (GIS). *CivilEng*, 3 (4), 895-908. https://doi.org/10.3390/civileng3040051

Beheshti, F., Tajbakhsh Fakhrabadi, S.M. & Shahidi, A. (2022). Evaluating the effect of water harvesting methods on urban run-off (Case study: Birjand rban watershed). *Journal of Rainwater Catchment Systems*, 10 (1), 1-12. [In Persian] https://dor.isc.ac/dor/20.1001.1.24235970.1401.10.1.3.2

Blume, T., Erwin, Z. & Bronstert, A. (2007). Rainfall-run-off response, event-based run-off coefficients and hydrograph separation. *Hydrological Sciences Journal*, 52 (5), 843-862. https://doi.org/10.1623/hysj.52.5.843

Burszta-Adamiak, E. & Przybylska, A. (2024). The potential for sustainable rainwater management through domestic rainwater harvesting based on real rainfall. *Journal of Water and Land Development*, 62 (VII–IX), 37-43. https://doi.org/10.24425/jwld.2024.150279

Cameron, R.W. & Blanusa, T. (2016). Green infrastructure and ecosystem services – is the devil in the detail? *Annals of Botany*, 118 (3), 377-391. https://doi.org/10.1093/aob/mcw129

Cauteruccio, A. & Lanza, L.G. (2022). Rainwater harvesting for urban landscape irrigation using a soil water depletion algorithm conditional on daily precipitation. *Water*, ١٤ (٢١), ٣٤٦٨. https://doi.org/١٠,٣٣٩٠/w١٤٢١٣٤٦٨

Chamani, R., Moradi Rekab Kalaei, H., Gholami, M. & Naghdi, M. (2022). Self-sufficiency of urban water in non-drinking uses by rainwater extraction method in Aryan Shahr, South Khorasan. *Journal of Rainwater Catchment Systems*, 9 (4), 43-52. [In Persian] https://dor.isc.ac/dor/20.1001.1.24235970.1400.9.4.2.0

Chiu, Y.-R., Aghaloo, K. & Mohammadi, B. (2020). Incorporating rainwater harvesting systems in iran's potable water-saving scheme by using a GIS-simulation based decision support system. *Water,* 12 (3), 752. https://doi.org/10.3390/w12030752

Croy, W., Moyle, B.D. & Moyle, C.-l.J. (2020). Perceived benefits of parks: the roles of information source exposure and park use. *Journal of Sustainable Tourism*, 28 (11), 1723-1742. https://doi.org/10.1080/09669582.2020.1757683

De Bell, S., White, M., Griffiths, A., Darlow, A., Taylor, T., Wheeler, B. & Lovell, R. (2020). Spending time in the garden is positively associated with health and wellbeing: results from a national survey in England. *Landscape and Urban Planning*, 200, 103836. https://doi.org/10.1016/j.landurbplan.2020.103836

Design Criteria for Urban and Rural Water Transmission and Distribution Systems. (2023). Publication No. 117-3, Second Edition. Hydropower Technical Systems, Operation, and Dispatching Development Office, Iran Water Management Company, Ministry of energy.

Gavit, B.K., Purohit, R.C., Singh, P.K., Kothari, M. & Jain, H.K. (2018). Rainwater harvesting structure site suitability using remote sensing and GIS. In: Singh, V., Yadav, S., Yadava, R. (eds) Hydrologic Modeling. Water Science and Technology Library, vol 81. Springer, Singapore. https://doi.org/10.1007/978-981-10-5801-1_23

Halder, S. & Bose, S. (2024). Addressing water scarcity challenges through rainwater harvesting: A comprehensive analysis of potential zones and model performance in arid and semi-arid regions–A case study on Purulia, India. *HydroResearch*, 7, 201-2012. https://doi.org/10.1016/j.hydres.2024.04.001

Hatibu, N., Mutabazi, K., Senkondo, E.M. & Msangi, A.S.K. (2006). Economics of rainwater harvesting for crop enterprises in semi-arid areas of East Africa. *Agricultural Water Management*, 80 (1-3), 74-86. https://doi.org/10.1016/j.agwat.2005.07.005

Helmreich, B. & Horn, H. (2009). Opportunities in rainwater harvesting. *Desalination*, 248 (1-3), 118-124. https://doi.org/10.1016/j.desal.2008.05.046

Jacque, H., Knox, J.W., Gush, M. & Holman, I.P. (2023). Modelling the potential of rainwater harvesting to improve the sustainability of landscape and public garden irrigation. *Journal of Environmental Management*, 348, 119167. https://doi.org/10.1016/j.jenvman.2023.119167

Kahinda, J.M., Rockstrom, J., Taigbenu, A.E. & Dimes, J. (2007). Rainwater harvesting to enhance water productivity of rainfed agriculture in the semi-arid Zimbabwe. *Physics and Chemistry of the Earth, Parts A/B/C*, 32 (15-18), 1068-1073. https://doi.org/10.1016/j.pce. 2007.07.011

Kanno, G.G., Lagiso, Z.A., Abate, Z.G., Areba, A.S., Gondol, B.N., Temesgen, H., Van Wyk, R. & Aregu, M.B. (2021). Estimation of rainwater harvesting potential for emergency water demand in the era of COVID-19. The case of Dilla town, Southern, Ethiopia. *Environmental Challenges*, 3, 100077. https://doi.org/10.1016/j.envc.2021.100077

Machado, R.E., Cardoso, T.O. & Mortene, M.H. (2022). Determination of run-off coefficient (C) in catchments based on analysis of precipitation and flow events. *International Soil and Water Conservation Research*, 10 (2): 208-216. https://doi.org/10.1016/j.iswcr.2021.09.001

Mahmoud, S.H., Adamowski, J., Alazba, A.A. & El-Gindy, A.M. (2016). Rainwater harvesting for the management of agricultural droughts in arid and semi-arid regions. *Paddy and Water Environment*, 14 (1), 231-246. https://doi.org/10.1007/s10333-015-0493-z

Mahtabi, G. & Taran, F. (2017). Investigating the effect of slope on run-off coefficient of surfaces with different materials under natural rainfall. *Iranian Journal of Irrigation and Drainage*, 11 (1), 35-45. [In Persian]

Mahtabi, G. & Taran, F. (2018). Comparing the effect of climate condition on tourism calendar in arid and humid cities using Holiday Climate Index (HCI) (Case study: Isfahan and Rasht). *Desert*, 23 (1), 63-73. https://doi.org/10.22059/jdesert.2018.66351

Maller, C., Townsend, M., Pryor, A., Brown, P. & St Leger, L. (2006). Healthy nature healthy people: 'contact with nature' as an upstream health promotion intervention for populations. *Health Promotion International*, 21 (1), 45-54. https://doi.org/10.1093/heapro/dai032

Moyle, B.D. & Weiler, B. (2017). Revisiting the importance of visitation: public perceptions of park benefits. *Tourism and Hospitality Research*, 17 (1), 91-105. https://doi.org/10.1177/1467358416638918

Opare, S. (2012). Rainwater harvesting: an option for sustainable rural water supply in Ghana. *Geojournal*, 77 (5), 695-705. https://doi.org/10.1007/s10708-011-9418-6

Pan American Health Organization (PAHO) (2017). Smart Hospitals Toolkit. Washington, D.C. Parker, A., Cruddas, P., Rowe, N., Carter, R. & Webster, J. (2013). Tank costs for domestic rainwater harvesting in East Africa. In: Proceedings of ICE: Water Management. https://ui.adsabs.harvard.edu/link_gateway/2013ICEWM.166..536P/doi:10.1680/wama.11.00113

Park, D.G., Sandoval, N., Lin, W., Kim, H. & Cho, Y.H. (2014). A case study: evaluation of water storage capacity in permeable block pavement. *KSCE Journal of Civil*

Engineering, 18 (2), 514-520. https://doi.org/10.1007/s12205-014- 0036-y

Rostami Khalaj, M., Rahmati, O., Dastranj, A. & Noor, H. (2020). Identification areas with inundation potential for urban run-off harvesting using the support vector machine model. *Journal of Rainwater Catchment Systems*, 8 (3), 1-10. [In Persian] https://dor.isc.ac/dor/20.1001.1.24235970.1399.8.3.1.0

Saeedi, I. & Goodarzi, M. 2020. Rainwater harvesting system: a sustainable method for landscape development in semiarid regions, the case of Malayer University campus in Iran. *Environ Dev Sustain,* 22 (2), 1579-1598. https://doi.org/10.1007/s10668-018-0218-8

Shi, P.-J., Yuan, Y., Zheng, J., Wang, J.-A., Ge, Y. & Qiu, G.-Y. (2007). The effect of land use/cover change on surface run-off in Shenzhen region, China. *Catena*, 69 (1), 31-35. https://doi.org/10.1016/j.catena.2006.04.015

Taran, F. & Mahtabi, G. (2016). Investigation of supplying water requirements in different parts of a city through rainwater harvesting; a case study: Bonab, Iran. *Irrigation and Water Engineering*, 7 (1), 40-53. [In Persian]

Vilane, B. & Mwendera, E. (2011). An inventory of rainwater harvesting technologies in Swaziland. *African Journal of Agricultural Research*, 6 (6), 1313-1321. https://doi.org/10.5897/ AJAR09.117

Wei, H., Li, J.-L. & Liang, T.-G. (2005). Study on the estimation of precipitation resources for rainwater harvesting agriculture in semi-arid land of China. *Agricultural Water Management*, 71 (1), 33-45. https://doi.org/10.1016/j.agwat.2004.07.002

Wesseling, J.G., Adham, A., Riksen, M.J.P.M., Ritsema, C.J., Oostindie, K. & Heidema, N. (2021). A Microsoft excel application to simulate water harvesting in a catchment. *Water Harvesting Research*, 4 (1), 1-18. https://doi.org/10.22077/jwhr.2021.2988.1032

Wurthmann, K. (2019). Assessing storage requirements, water and energy savings, and costs associated with a residential rainwater harvesting system deployed across two counties in Southeast Florida. *Journal of Environmental Management*, 252, 109673. https://doi.org/ 10.1016/j.jenvman.2019.109673

Yifru, B.A., Kim, M.-G., Lee, J.-W., Kim, I.-H., Chang, S.-W. & Chung, I.-M. (2021). Water storage in dry riverbeds of arid and semi-arid regions: overview, challenges, and prospects of sand dam technology. *Sustainability*, 13 (11), 5905. https://doi.org/10.3390/ su13115905

Zhong, Q., Tong, D., Crosson, C. & Zhang, Y. (2022). A GIS-based approach to assessing the capacity of rainwater harvesting for addressing outdoor irrigation. *Landscape and Urban Planning*, 223, 104416. https://doi.org/10.1016/j.landurbplan.2022.104416

Original Article

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Evaluation of hybrid metaheuristic models in estimating electrical conductivity (case study: Kakarza river, Lorestan province)

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Abstract

Electrical conductivity (EC) is an important indicator for monitoring water quality in rivers. Electrical conductivity is inherently related to the concentration of dissolved ionic compounds in aquatic environments, including various salts and minerals. Estimating electrical conductivity is crucial for environmental monitoring and assessing the health of aquatic ecosystems. In this study, a hybrid intelligent model based on the support vector regression approach was developed to estimate the electrical conductivity of river water. For this purpose, three optimization algorithms, including wavelet, whale, and particle swarm optimization , were utilized for modeling the electrical conductivity of river flow. For modeling, data and statistics from the Kakareza hydrometric station located in Lorestan province were used as a case study in seven combined scenarios consisting of input parameters for the years 2003-2023. To evaluate the performance of the models, criteria such as correlation coefficient, root mean square error, mean absolute error, and Nash-Sutcliffe coefficient were employed. The results indicated that increasing the amount of effective parameters in the modeling process improves the results. Furthermore, the results obtained from the evaluation criteria showed that the wavelet support vector regression model had a correlation coefficient of 0.980, a root mean square error of 0.344 (ppm), a mean absolute error of 0.172 (ppm), and a Nash-Sutcliffe coefficient of 0.85 during the validation phase. Overall, the findings indicated that the use of intelligent models based on the support vector regression approach can serve as an effective method for the sustainability of river engineering.

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Introduction

Clean and healthy water is essential for human consumption, hygiene, and health maintenance. Contaminated water harbors harmful microorganisms, pathogens, and pollutants that cause waterborne diseases (Nemčić-Jurec et al., 2022). Water quality is essential for maintaining the health of aquatic ecosystems, including rivers, lakes, wetlands, and oceans. Aquatic organisms, such as fish, plants, and other wildlife, depend on clean water for survival and growth. Polluted water, containing chemicals, toxins, or excessive nutrients, can lead to habitat destruction, species loss, and the disruption of ecological balance (Bhat et al., 2022). Water quality is crucial for agriculture and food production. Contaminated water used for irrigation negatively impacts the health and productivity of agricultural products. It also leads to the accumulation of harmful substances in food, posing risks to human health. Maintaining good water quality in irrigation systems is crucial for sustainable agriculture and safe food production (Mensah-Akutteh et al., 2022). Water quality is of paramount importance for human health, ecosystem function, sustainable development, and various economic activities. Monitoring, managing, and maintaining water quality are vital for protecting human health, safeguarding the environment, and ensuring the sustainable use of this valuable resource (Giri et al., 2022).

Electrical Conductivity (EC) is an important parameter used to assess and monitor water quality. It is a measure of the water's ability to conduct electrical current and is influenced by the concentration of dissolved ions in the water (Naiel et al., 2022). Electrical conductivity serves as an estimate of the concentration of Total Dissolved Solids (TDS) in water. TDS represents the total concentration of dissolved mineral and organic substances in water, including salts, minerals, metals, and other dissolved solids. Higher electrical conductivity values generally indicate elevated TDS levels, which can affect the taste, odor, and overall palatability of the water (Ezea et al., 2022). High electrical conductivity values also indicate higher levels of salinity, which can have adverse effects on aquatic life, irrigation practices, and the suitability of water for various uses (Liu et al., 2023). Measuring and predicting electrical conductivity can aid in identifying identify potential sources of pollution and assess overall water quality (Lakrout et al., 2022).

Accurate measurement of electrical conductivity in the laboratory is challenging, time-consuming, and requires skilled manpower, and also involves high costs. Nowadays, Given thenonlinear and complex nature of river water quality issues, artificial intelligence approaches are increasingly being used. These models are inspired by the nature of living organisms and are capable of solving problems with great complexity and scope. These models have garnered significant attention from researchersin the field of predicting the qualitative parameters of rivers, particularlyelectrical conductivity, which can be mentioned below. Machine learning algorithms offer a promising approach to address these challenges and enhance the accuracy and efficiency of EC prediction. Khadr & Elshemy (2017) investigated the capabilities of the support vector regression model in comparisonto empirical models for predicting various water quality factors based on electrical conductivity, turbidity, discharge, water temperature, dissolved oxygen, total suspended solids, total dissolved solids, and pH parameters. The results showed that artificial intelligence models have higher accuracy than empirical models. Najah Ahmed et al. (2019) used support vector regression and artificial neural network models to predict surface water electrical conductivity in the Johor river basin. The results showed that the support vector regression model has less error rates compared to conventional models such as artificial neural networks. Similarly, Ekemen Keskin et al. (2020) used machine learning and regression-based techniques to predict groundwater electrical conductivity. The results demonstrated that models based on the machine learning approach, especially support vector regression, are suitable models for predicting electrical conductivity. Mokhtar et al. (2022) used multiple regression and support vector regression models to predict the electrical conductivity of the Mead River in Turkey. The results showed that the support vector regression model is more accurate than statistical models. showed for predicting the irrigation water quality index. These models served as rapid decision-making tools for modeling irrigation water quality and assisting in water resource management strategies. Kumar et al. (2023) used a hybrid support vector regression model combined with metaheuristic algorithms to predict the electrical conductivity of the Ganges River in India. The results showed that the hybrid support vector regression model with metaheuristic algorithms performs better than the single support vector regression model.

Wang et al. (2024) conducted a study comparing hybrid models based on support vector regression performance against single models for predicting water quality in the Jinqing River in China. The results showed that hybrid models outperformed single models. Shams et al. (2025) compared hybrid models including random forest, extreme gradient boosting, gradient boosting, adaptive boosting, K-Nearest neighbors regression, decision tree regression, support vector regression, and multi-layer perceptron regression with metaheuristic algorithms to predict river water quality in India. The results indicated that Support Vector Regression had higher accuracy compared to the other models studied.

Overall, considering the research conducted, the effectiveness of artificial intelligence models in estimating river water quality and other water resources studies has been confirmed. Therefore, artificial intelligence models, including support vector regression, can be used as an efficient tool for estimating river water quality and hydrological issues. In recent years, numerous studies have been conducted on the use of single support vector regression for modeling river water quality, and the results have been associated with reduced model accuracy (Rajaee et al., 2022). Nowadays, in order to increase accuracy, reduce error, and improve the efficiency of the support vector regression model, combining this model with metaheuristic optimization algorithms has been used as a suitable solution for predicting river water quality, which has yielded favorable results (Jalalkamali & Jalalkamali, 2018). In this study, hybrid models of support vector regression-wavelet, support vector regression-whale optimization algorithm, and support vector regression-particle swarm optimization were used to model the water quality of the Kakarza River located in Lorestan Province. The Kakarza River is one of the important rivers in Lorestan Province in terms of agriculture, drinking water, and aquaculture. Given that the water quality of this river has faced problems in recent years, such that the water quality of this river has decreased annually in the past, endangering the health of living organisms. Therefore, the analysis and investigation of the water quality of the Kakarza River is necessary considering the economic investment conditions, aquaculture production, tourism, and special geographical location of Lorestan Province's planning. On the other hand, although the use of support vector regression has been widely used to predict river quality. So far, no research has been done on the use and comparison of whale and particle swarm metaheuristic algorithms in this region. Therefore, in this research, optimization algorithms were used with the aim of combining with the support vector regression model to estimate the electrical conductivity of the Kakarza River.

Materials and Methods

Study Area

The study area is the Kakarda Station, located in Lorestan Province. This station is situated along the Kakarda River, which is one of the permanent rivers in Lorestan Province. It originates from the southeastern mountains of Alishtar County and the Chaghalondi (Harood) district, and is known as Kakarda within the boundaries of Alishtar County. The river is located between 48°15' to 49° latitude and 32° 22' to 33° 52' north latitude, in Lorestan Province, to the east of Khorramabad County, and forms part of the tributaries of the Karkheh River in the Zagros region. The Kakarda River lies at an elevation of 1550 meters above sea level. The catchment area of Kakarda spans 1148 square kilometers and features a river that is 85 kilometers long. After merging with the Kashkan, Simreh, and Karkheh rivers, the Kakarda River ultimately flows into the Persian Gulf. Figure 1 illustrates the geographical location of the study area. In this research, to model the electrical conductivity of the Kakarda River in Lorestan Province, monthly data, including sodium, magnesium, calcium, sulfate, chloride, bicarbonate, and pH, were used for the statistical period of 2003-2023. Table 1 presents the statistical characteristics of the parameters used.

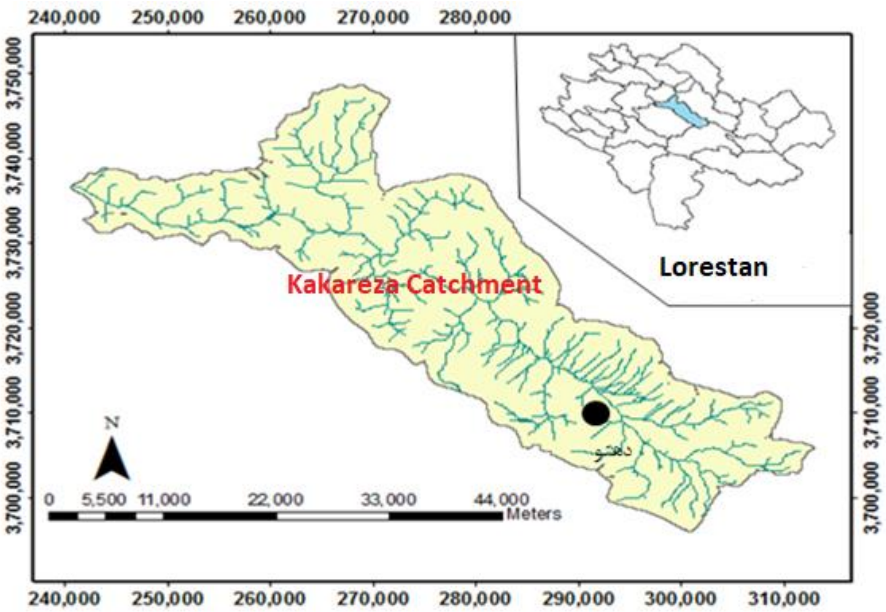

Fig 1. Study Area

Table 1. Statistical Characteristics of the Parameters Studied

Parameters	Training			Testing		
	Minimum	Mean	Maximum	Minimum	Mean	Maximum
Na(mg/l)	0.02	0.215	0.81	0.06	0.22	0.45
Mg(mg/l)	0.30	1.18	3.70	0.50	1.22	3.60
Ca(mg/l)	1	2.37	4.49	1.9	2.97	4.50
SO_4(mg/l)	0	0.40	3.74	0.03	0.56	2.43
Cl(mg/l)	0.1	0.28	1	0.21	0.39	1
HCO_3(mg/l)	1.25	3.05	5.80	1.90	3.43	5.30
PH	6.6	7.80	8.57	6.90	7.99	8.30
EC (ds/m)	180	380.10	675	180	390.72	632

Methods

In this study, the data used initially included Electrical Conductivity (EC), Bicarbonate (HCO3), Chloride (Cl), Sulfate (SO4), Calcium (Ca), Magnesium (Mg), Sodium (Na), and the concentration of hydrogen ions (pH) measured monthly at the Kakarza hydrometric station located in Lorestan Province during the years 2003-2023, obtained from the Lorestan Province Regional Water Company. It is worth noting that during the period under review, the time series data had no missing data, were homogeneous, and did not contain outliers. Then, in order to integrate statistics and information, a normalization process was performed on the input data obtained. Nowadays, due to the increased efficiency of intelligent models, including support vector regression, optimization algorithms are used to optimize the tuning parameters of the model. In this study, wavelet, whale optimization algorithm, and particle swarm optimization algorithms were used to optimize the tuning parameters of the support vector regression model. The support vector regression model has kernel or activation functions, and these functions consist of variables t, d, and δ. In the process of hybridizing the model, these variables are estimated to the most optimal value possible by the aforementioned optimization algorithms. Then, the hybrid model structure is formed, and finally, the input parameters are entered into the model, leading to the output response. Overall, the model results are examined based on evaluation criteria and time series plots, box plots, and Taylor diagrams. The models and algorithms under review are briefly described below.In this study, water quality data from the river during the years 2003 to 2023 was used, such that 80% of the data from 2003 to 2018 was randomly selected for training, and the remaining 20% from 2019 to 2023 was used for testing. Additionally, for the training process of the model, a total of 1000 iterations were considered, and this model was implemented in MATLAB. The flowchart of the research is shown in the Figure 2.

Support vector regression

Support vector regression is an artificial intelligence method based on optimization theory and follows the principle of minimizing error, which leads to a global optimal solution (Vapnik, 1995). In the SVR model, which includes a function with dependent variables Y, the dependent variable is composed of several independent variables X and an error term. As observed in regression problems, there is an algebraic relationship between the dependent and independent variables, as shown below in the structure of the Support Vector Regression model (Vapnik, 1998).

$$f(x)=W^{T}.\emptyset(x)+b \quad (1)$$

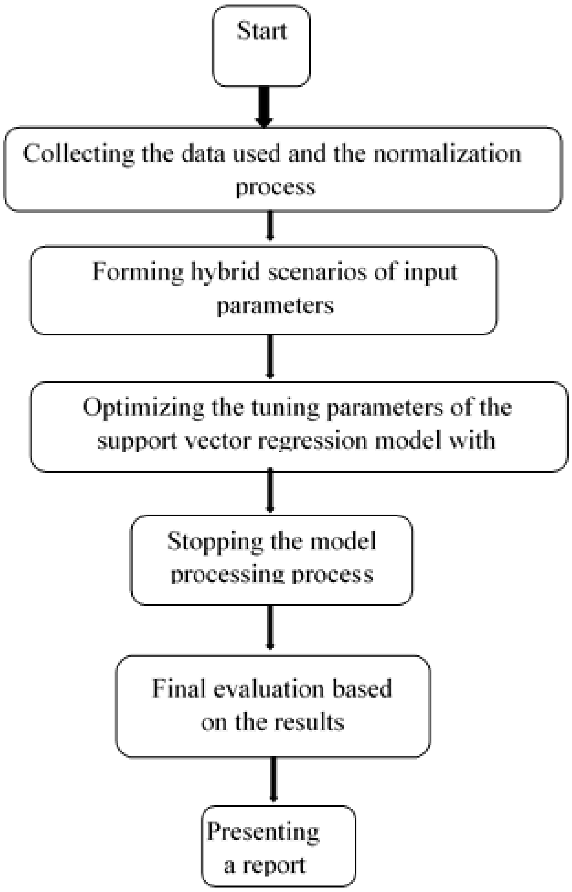

Fig 2. The research flowchart

$$y=f(x)+noise \tag{2}$$

Like other artificial intelligence models, support vector regression has activation functions called kernels. These kernels include the polynomial kernel, Radial Basis Function (RBF) kernel, and linear kernel, and are estimated according to the following relationships (Vapnik & Chervonenkis, 1991; Basak et al., 2007). These three kernel functions were also used in this research. The support vector regression model was also coded in MATLAB software.

$$k(x,x_j)=(t+x_i.x_j)^d \tag{3}$$

$$K(x,x_i)=\exp\left(-\frac{\|x-x_i\|^2}{2\sigma^2}\right) \tag{4}$$

$$k(x,x_j)=x_i.x_j \tag{5}$$

Wavelet Transform

Wavelet transform has been presented as an alternative method to the short-time Fourier transform, and its goal is to overcome the issues related to frequency resolution in the short-time Fourier transform. In the wavelet transform, similar to the short-time Fourier transform, the signal of interest is divided into windows, and the wavelet transform is performed separately on each of these windows (Vapnik, 1998). However, the most important difference between them is that in the wavelet transform, in addition to the frequency resolution of a signal or window length changing according to the type of frequency, the width of the window or the frequency scale also changes according to the type of frequency. In other words, in wavelet transform, scale exists instead of frequency. Therefore, the wavelet transform is a type of time-scale transformation. Accordingly, using the wavelet transform, at higher scales, the signal is expanded, allowing detailed analysis of the signal, while at lower scales, the signal is compressed, enabling examination of the overall structure of the signal (Wang et al, 2000). A wavelet, meaning 'small wave', is a segment or window of the original signal that concentrates its energy in time. Using wavelet transform or analysis, one can decompose a parent signal or time series into wavelets with different resolution levels and scales. Thus, wavelets are transferred and decomposed samples of the parent signal that exhibit oscillations over a finite length and are highly localized. Based on this important property of the wavelet transform, non-stationary and transient time series can be analyzed locally (Shin et al, 2005).

In this research, various wavelet functions, including Haar, Mexican Hat, and Morlet, were used. The Morlet wavelet function was selected because it is the second derivative of the Gaussian function, which yields better performance. The Morlet wavelet transform, with its ability to provide precise time-frequency analysis, adjustable central frequency, suitable shape for analyzing vibrational signals, and capability for extracting phase information, is a powerful tool for signal analysis in various domains, even capable of removing noise from signals. Noise removal methods based on wavelets generally perform better than traditional methods because they can eliminate noise without losing important details of the signal

Particle Swarm Optimization

The Particle Swarm Optimization algorithm is a metaheuristic algorithm that was first introduced by Kennedy and Eberhart (1995). These researchers first examined computational intelligence based on social relations, then conducted these studies on groups of animals and humans, and finally, this algorithm was inspired by the nature of the behavior of birds and fish. This algorithm is inspired by the collective behavior of a group of birds or fish. Like other optimization algorithms, this algorithm helps a group of birds and fish find the most suitable path to reach the nest and food without obstructing the movement of other particles. The steps of this algorithm in this research are such that the initial population is first generated, the velocity vectors of the particles are initially zero, and the location vector is randomly selected. In the next step, the value of the particle is evaluated, and then the best individual position and velocity of the particle are updated (Shrivatava et al., 2015). The flowchart of this algorithm is shown in the Figure 3.

Whale Optimization Algorithm

The Whale Optimization Algorithm is a metaheuristic algorithm inspired by the nature and behavior of living organisms and is used in various fields. It was first introduced by Mirjalili and Lewis (2016). This algorithm originates from the behavior of whales during hunting, in such a way that the whale identifies the hunting location and surrounds it. In this algorithm, it is assumed that the most suitable solution is to hunt the target. In this algorithm, after the best hunting target is searched, other search agents try to update their location relative to the best prey (Reddy & Saha, 2022). The behavior of this algorithm follows the following relationships:

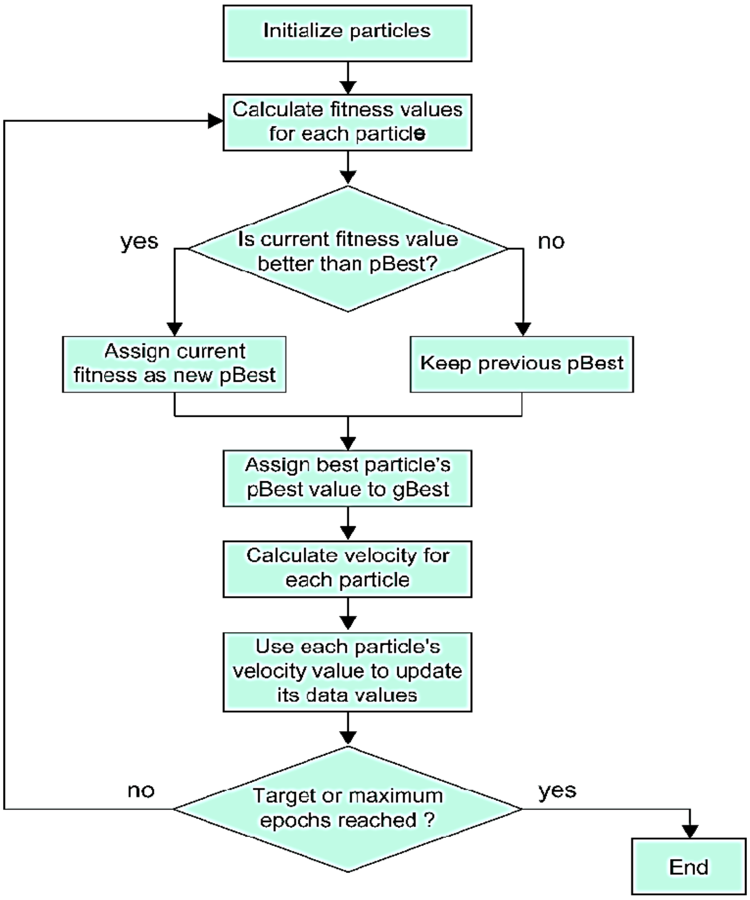

Fig 3. Flowchart of the particle swarm algorithm

$$\vec{D} = |\vec{C}.\vec{X} - \vec{X}(t)| \quad (6)$$

$$\vec{X}(+1) = \vec{X^*}(t) - \vec{A}.\vec{D} \quad (7)$$

"where A and C are coefficient vectors, X^* is the position vector of the best solution obtained so far, and X is the position vector. The vectors C and A are calculated as follows:"

$$\vec{A} = 2\vec{a}.\vec{r} - \vec{a} \quad (8)$$

$$\vec{C} = 2\vec{r} \quad (9)$$

In the above formulas, 'a' linearly decreases from a value between 2 and 0 in each iteration, and 'r' is a random vector in the range of 0 to 1. The flowchart of this algorithm is shown in the Figure 4.

Evaluation criteria

In this study, the following evaluation indices were used to evaluate the models under investigation for simulating the discharge of rivers in the Dez watershed

$$R=\frac{\sum_{i=1}^{N}(x_i-\bar{x})\,(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{N}(x_i-\bar{x})^2\,\sum_{i=1}^{N}\,(y_i-\bar{y})^2}} \quad 1\leq R\leq 1 \quad (10)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - y_i)^2} \quad (11)$$

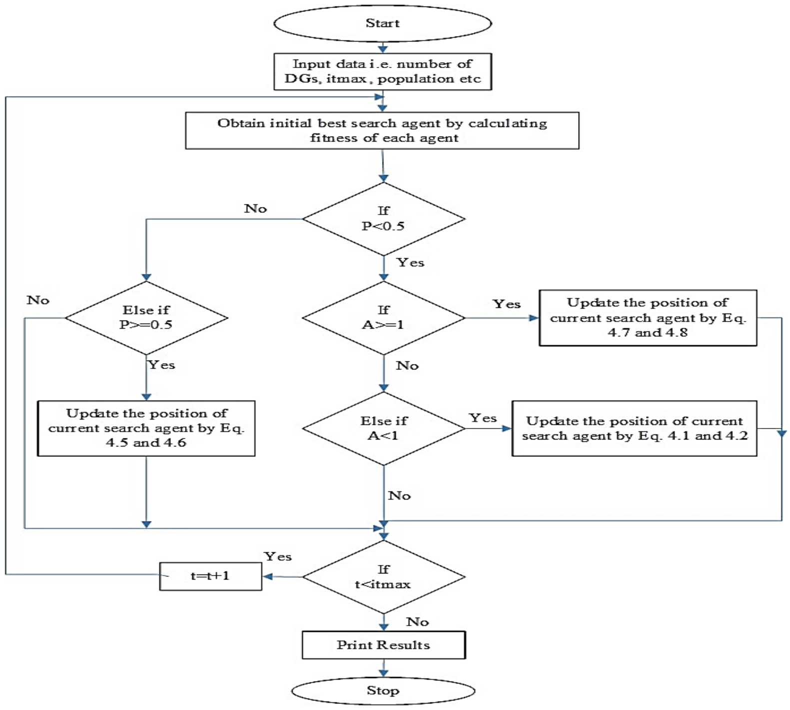

Fig 4. Whale algorithm flowchart

$$MAE = \frac{\sum_{i=1}^{n}|x_i - y_i|}{n} \quad (12)$$

$$NS = 1 - \frac{\sum_{i=1}^{N}(x_i - y_i)^2}{\sum_{i=1}^{N}(x_i - \bar{y})^2} \quad \infty \le NS \le 1 \quad (13)$$

In the above relations, R is the correlation coefficient, RMSE is the root mean square error in $m^3/sm^3/s$, and NS is the Nash-Sutcliffe efficiency. x_i and y_i represent the observed and computed values at the i-th time step, respectively. N is the number of time steps, while and are the mean values of the observed and computed data, respectively. In addition to these metrics, scatter plots and time series graphs of the observed-computed values over time are also used for further comparison and analysis.

Results and Discussion

In this study, a hybrid artificial intelligence method based on the Support vector regression model with whale optimization algorithm, and particle swarm optimization were used to model the electrical conductivity of the Kakarza River. Data from the Kakarza station located in Lorestan Province was used for modeling. The parameters Sodium (Na), Magnesium (Mg), Calcium (Ca), Sulfate (SO_4), Chloride (Cl), Bicarbonate (HCO_3), and pH were selected as inputs, and the Electrical Conductivity (EC) parameter was selected as the model output, with monthly data spanning from 2003 to 2023. Given the complex and non-linear nature of river electrical conductivity and the various parameters affecting it, a combination of effective parameters under different scenarios is necessary (Nagy et al., 2002; Kisi et al., 2006). Table 2 shows the combination of effective parameters under different scenarios. It is worth mentioning that for modeling, 80% of the input data was used for training and the remaining 20% was used for testing.

To model the electrical conductivity of the Kakarza River flow, the Support vector regression model with wavelet, whale optimization algorithm, and particle swarm optimization algorithms were used. In the support vector regression model, kernel functions were also used, including Radial Basis Function (RBF), polynomial, and linear functions, which were investigated in this study. For this purpose, the values of the quality parameters of the Kakarda hydrometric station were normalized and then entered into the support vector regression model. In recent years, because the parameter values of the kernel functions in the support vector regression model are selected randomly, optimization algorithms have been used to increase accuracy and reduce model error (Dehghani et al., 2020). In this study, wavelet, whale optimization algorithm, and Particle Swarm Optimization algorithms were also used to improve the performance of the model in order to optimize the values of the tuning parameters. Therefore, in this study, after entering the input parameter information into the model and optimizing the tuning parameters, the hybrid model structure is formed, leading to the computational response of the model. Since the stopping criterion in training artificial intelligence models is the amount of error, the model stops at the lowest amount of error and the output is obtained.

In Table 3, the estimated values of the tuning parameters using wavelet, whale, and particle swarm optimization algorithms are shown. In Table 4, the sensitivity analysis or the impact of each of the input parameters according to the selected scenarios is shown. As observed, in scenario one, the effect of magnesium on sodium has improved the model's performance. Additionally, in the fourth scenario, the inclusion of sulfate has also significantly changed the model's performance compared to other scenarios, and it has shown a suitable accuracy in scenario seven. Therefore, in this research, the results of scenario seven have been discussedAs shown in Table 5, the hybrid models in scenario number 7, which includes all input parameters to the model, have better performance than the other scenarios. Also, all models in the Radial Basis Function kernel have better accuracy, and the results of the models according to the combined scenarios are shown in Table 5 with the Radial Basis Function kernel. As shown in the table, the support vector regression-wavelet model in the combined scenario number 7 has the highest correlation coefficient of 0.980, the lowest root mean square error of 0.344 (ppm) , the lowest mean absolute error of 0.172 (ppm) , and the highest Nash-Sutcliffe coefficient of 0.985 in the validation stage, shows better performance.

Figure 5 shows the time series chart of observed and calculated values. As observed, the support vector regression-wavelet model shows acceptable accuracy in estimating most points, including minimum, maximum, and median, compared to the hybrid support vector regression-whale and support vector regression-particle swarm models. Also, the support vector regression-whale and particle swarm models have relatively good performance in estimating median values and performed poorly in estimating minimum and maximum values.

In Figure 6, the box plot of the models under study is shown. As observed, the support vector regression-wavelet model shows better performance in estimating the first quartile and median values compared to the observed data, while the support vector regression-particle swarm model performed poorly, and the support vector regression-whale model also has good accuracy and is in second place.

In Figure 7, the Taylor diagram of the models under study is visible. The support vector regression-wavelet model has better performance because the standard deviation of the predicted electrical conductivity of the river flow has the closest distance to the standard deviation of the observed data and the correlation coefficient also shows the highest value.

As shown in Figures 6 and 7, the support vector regression-wavelet model has a good performance because the range of computed values is close to the estimated observed values. Additionally, the first and third quartile values have been estimated in such a way that it has resulted in a high standard deviation for this model. However, the support vector regression-particle swarm model has not covered the range of computational data adequately, and its standard deviation is lower compared to the other models

The support vector regression model - whale algorithm is a discrete optimization that reduces the time to reach an optimal solution in a wide search area because it avoids local optimal solutions. This makes the algorithm suitable for solving non-linear problems with large dimensions with an appropriate speed in converging towards an acceptable optimal answer. These results are consistent with the research by Zeidalinejad & Dehghani (2023) and Dehghani et al. (2022) and Nohani et al (2025). it can be said that the hybrid model of support vector regression with the wavelet algorithm has a favorable ability because the wavelet algorithm divides the signal or time series into two categories, high-pass and low-pass, and in the high-pass category, it examines the details of the time series with high resolution at the minimum and maximum points, which improves the model results. In general, it is recommended to use the hybrid support vector regression-wavelet model as a model with negligible error to solve non-linear problems with large dimensions with an appropriate speed in convergence towards an optimal answer. It can also be used as a novel approach to predict the electrical conductivity of river water flow to make appropriate management decisions to improve water resources, prepare land, economic investment, and produce aquatic products.

Conclusion

Estimating the electrical conductivity of river water using hybrid models based on support vector regression serves as an effective tool in the design of hydrological systems and river engineering. In the present study, a case study was conducted to evaluate the performance of a hybrid metaheuristic model of support vector regression for estimating the electrical conductivity of the Kakarza River located in Lorestan Province. To achieve this, nature-inspired algorithms including wavelet, whale, and particle swarm optimization were combined with the Support vector regression model. Parameters such as Sodium (Na), Magnesium (Mg), Calcium (Ca), Sulfate (SO4), Chloride (Cl), Bicarbonate (HCO3), and pH were utilized as inputs, while electrical conductivity (EC) was used as the output parameter of the model. For constructing the hybrid support vector regression model, 80% of the data was allocated for training, and the remaining 20% was used for testing. To evaluate the models under consideration, statistical indicators such as correlation coefficient, Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Nash-Sutcliffe efficiency were employed. Furthermore, time series plots, box plots,

Table 2. Combination of Input Parameters

Number	Input	Output
1	Na	EC
2	Na, Mg	EC
3	Na, Mg, Ca	EC
4	Na, Mg, Ca,SO4	EC
5	Na, Mg, Ca,So4, Cl	EC
6	Na, Mg, Ca,So4, Cl, HCO3	EC
7	Na, Mg, Ca,So4, Cl, HCO3, PH	EC

Table 3. The values of the adjustment parameters of the studied algorithm

Alghorithm	t	d	δ
Wavelet	10	0.1	0.18
WOA	10	0.2	0.25
PSO	10	0.3	0.28

Table 4. The error rate of the input scenarios of the model during the training and testing phases

Senario	Training RMSE (ppm)	Testing RMSE (ppm)
1	0.643	0.441
2	0.618	0.422
3	0.601	0.411
4	0.584	0.393
5	0.561	0.377
6	0.545	0.362
7	0.521	0.344

Table 5. Results of the models under review

Model	Kernel	Training				Testing			
		R	RMSE (ppm)	MAE (ppm)	NS	R	RMSE (ppm)	MAE (ppm)	NS
WSVR	RBF	0.960	0.521	0.250	0.970	0.980	0.344	0.172	0.985
	Poly	0.951	0.534	0.261	0.960	0.970	0.352	0.185	0.975
	Line	0.940	0.547	0.273	0.950	0.955	0.368	0.197	0.960
WOA-SVR	RBF	0.945	0.540	0.270	0.955	0.960	0.355	0.191	0.965
	Poly	0.938	0.551	0.278	0.940	0.945	0.374	0.202	0.950
	Line	0.921	0.564	0.288	0.930	0.930	0.388	0.214	0.935
PSO-SVR	RBF	0.930	0.556	0.281	0.940	0.950	0.376	0.207	0.945
	Poly	0.922	0.562	0.290	0.930	0.935	0.389	0.218	0.935
	Line	0.912	0.575	0.301	0.920	0.921	0.398	0.227	0.927

and Taylor diagrams were used to analyze the results. Findings from the study, based on the evaluation of scenarios consisting of input parameters, indicated that increasing the number of effective parameters across different modeling scenarios resulted in better performance in estimating electrical conductivity. Additionally, the results from the evaluation criteria showed that the SVR-Wavelet model exhibited high accuracy and minimal error. According to the analyzed diagrams, the SVR-Wavelet model estimated electrical conductivity values closely resembling their actual values, which was evident in the box and Taylor plots. Overall, the results of

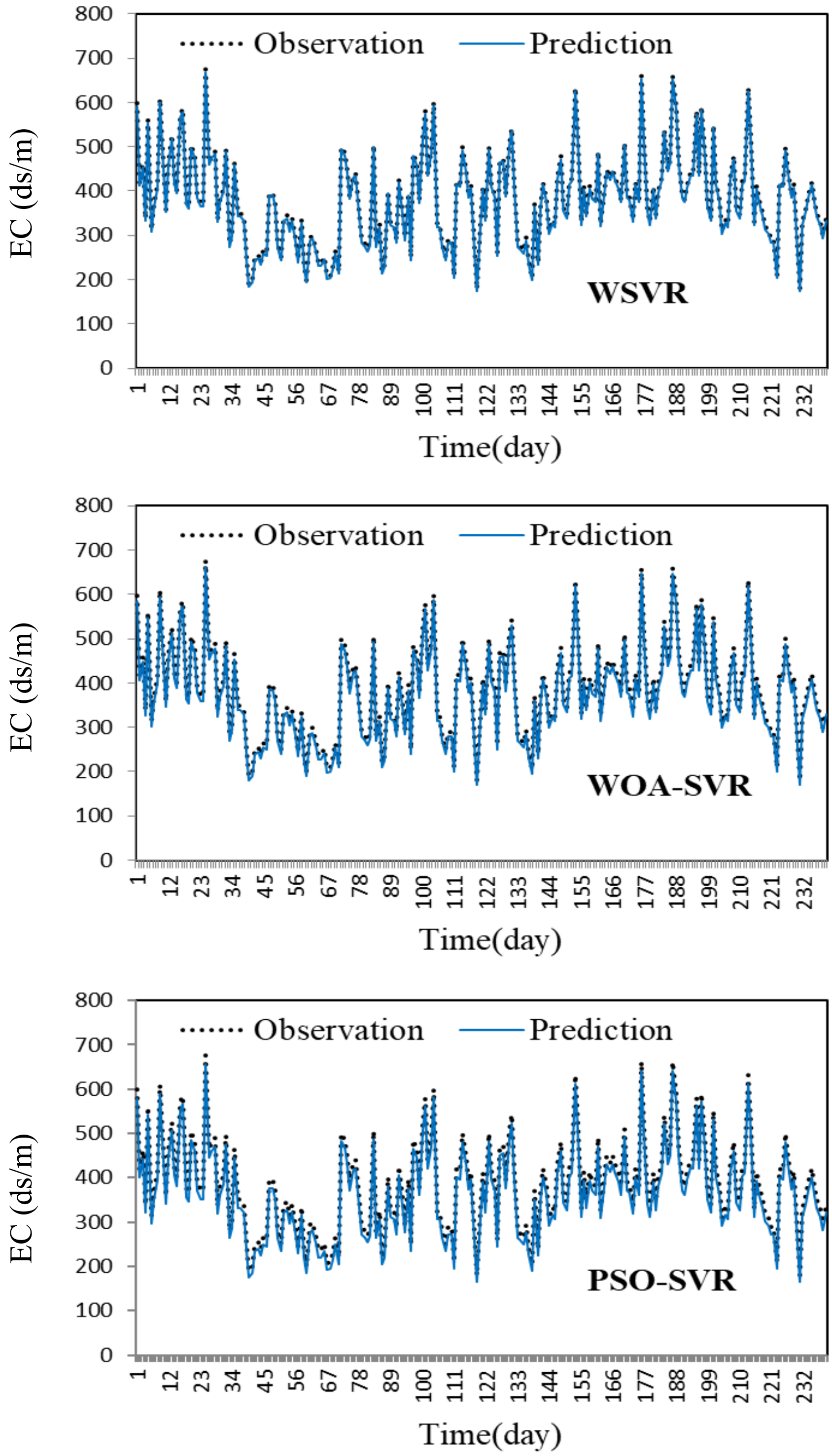

Fig 5. Time series chart of the models under review

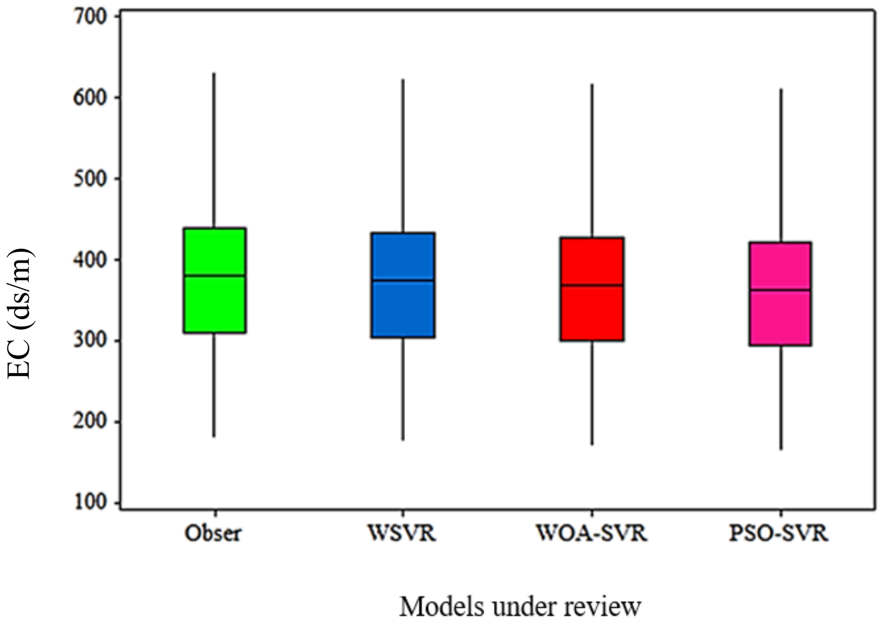

Fig 6. Box plot of the models under review

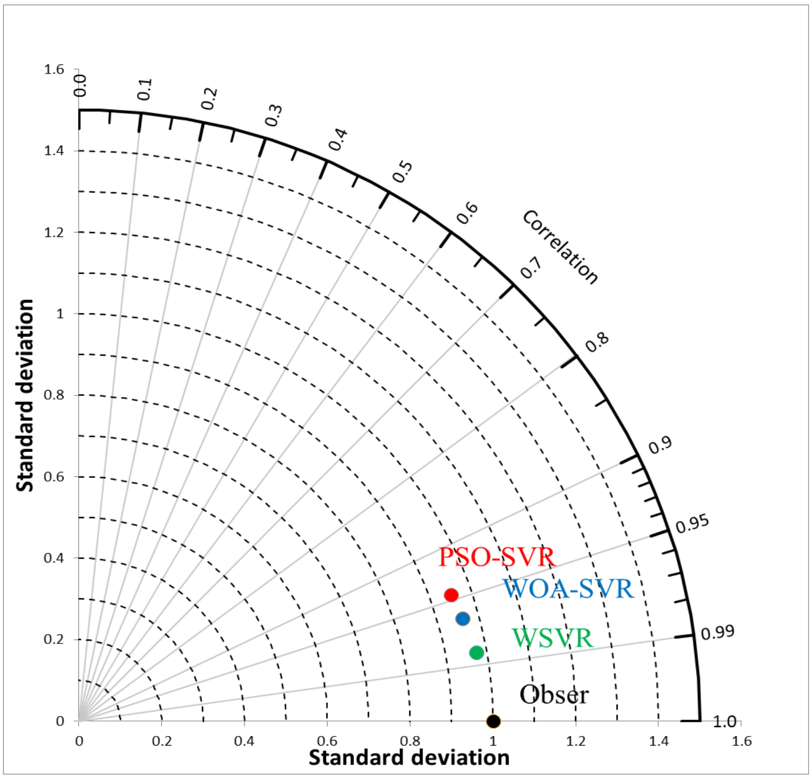

Fig 7. Taylor diagram of the models under review

this study demonstrate that the use of artificial intelligence models based on the support vector regression approach can be utilized for estimating the electrical conductivity of river water over a 20-year statistical timeframe for other regions of the country and is a step toward making appropriate management decisions.In conclusion, it is suggested to utilize new algorithms that combine continuous and discrete optimization, which do not get trapped in local optima, to improve model performance. Additionally, this modeling should be applied in other regions of the country.

References

Basak, D., Pal, S., & Patranabis, D.C. (2007). Support vector regression. *Neural Information Process,* 11(2), 203-225. https://doi.org/10.1007/978-1-4302-5990-9_4

Bhat, S.U., Nisa, A.U., Sabha, I., & Mondal, N.C. (2022). Spring water quality assessment of Anantnag district of Kashmir Himalaya: towards understanding the looming threats to spring ecosystem services. *Applied Water Science,* 12,180-198. https://doi.org/10.1007/s13201-022-01691-7

Dehghani, R., Babaali, H., & Zeidalinejad, N. (2023). Evaluation of statistical models and modern hybrid artificial intelligence in simulation of runoff precipitation process. *Sustainable Water Resources Management,* 8, 154-172. https://doi.org/10.1007/s40899-022-00743-9

Dehghani, R., Torabi Poudeh, H., Younesi, H., & Shahinejad, B. (2020). Daily streamflow prediction using support vector machine-artificial flora (SVM-AF) hybrid model. *Acta Geophysica,* 68(6), 51-66. https://doi.org/10.1007/s11600-020-00472-7

Eberhart, R., & Kennedy, J. (1995). A New Optimizer Using Particle Swarm Theory Proc. Sixth International Symposium on Micro Machine and Human Science, Nagoya, Japan, Piscataway, *NJ: IEEE Service Center* , 5, 39-43. 10.1109/MHS.1995.494215

Ekemen Keskin, T., Özler, E., & Şander, E. (2020). Prediction of electrical conductivity using ANN and MLR: a case study from Turkey. *Acta Geophysica,* 68, 811–820. https://doi.org/10.1007/s11600-020-00424-1

Ezea, V.C., Ihedioha, J.N., Abugu, H.O., & Ekere, N.R. (2022). A multi-criteria approach to drinking and irrigation water assessment of spring water in Igbo-Etiti. Nigeria *Applied Water Science,* 12, 220-241.https://doi.org/10.1007/s13201-022-01747-8

Giri, A., Bharti, V.K., Kalia, S., Kumar, K., & Khansu, M. (2022). Hydrochemical and quality assessment of irrigation water at the trans-himalayan high-altitude regions of Leh, Ladakh. India. *Applied Water Science,* 12,197-211. https://doi.org/10.1007/s13201-022-01716-1

Jalalkamali, A., & JalalKamali, N. (2018). Adaptive network-based fuzzy inference system-genetic algorithm models for prediction groundwater quality indices: a GIS-based analysis. *Journal of Artificial Intelligence & Data Mining,* 6(2), 439-445. https://doi.org/10.22044/jadm.2017.1086

Khadr, M., & Elshemy, M. (2017). Data-driven modeling for water quality prediction case study: the drains system associated with Manzala Lake. *Egypt Ain Shams Engineering Journal* , 8, 549–557. https://doi.org/10.1016/j.asej.2016.08.004

Kisi, O., Karahan, M., & Sen, Z. (2006). River suspended sediment modeling using fuzzy logic approach. *Hydrological Process*, 20(2), 4351-4362. https://doi.org/10.1002/hyp.6166

Kumar, D., Singh, V.K., Abed, S.A.,

Tripathi, V.K., Gupta, S., Al-Ansari, N., Vishwakarma, D.K., Dewidar, A., Al-Othman, A., & Mattar, M. (2023). Multi-ahead electrical conductivity forecasting of surface water based on machine learning algorithms. *Applied Water Science,* 13, 192-214. https://doi.org/10.1007/s13201-023-02005-1

Lakrout, A., Meddah, B., & Ali Rahmani, S.E. (2022). Geochemical assessment of thermal water in Bouhanifia aquifer system: suitability for touristic therapeutic treatment. *Applied Water Science,* 12, 204-221. https://doi.org/10.1007/s13201-022-01727-y

Liu, Z., Feng, S., & Zhang, D. (2023). Effects of precipitation, irrigation, and exploitation on groundwater geochemical evolution in the people's victory canal irrigation area. China *Applied Water Science,*13,1-18. https://doi.org/10.1007/s13201-022-01808-y

Mensah-Akutteh, H., Buamah, R., Wiafe, S., & Nyarko, K.B. (2022). Optimizing coagulation–flocculation processes with aluminium coagulation using response surface methods. *Applied Water Science,* 12,188-200. https://doi.org/10.1007/s13201-022-01708-1

Mirjalili, S., & Lewis, A. (2016). The whale optimization algorithm. *Advances in Engineering Software,* 95(6):51-67. https://doi.org/10.1016/j.advengsoft.2016.01.008

Mokhtar, A., Elbeltagi, A., & Gyasi-Agyei, Y. (2022). Prediction of irrigation water quality indices based on machine learning and regression models. *Applied Water Science,* 12,76-88. https://doi.org/10.1007/s13201-022-01590-x

Nagy, H., Watanabe, K., & Hirano, M. (2002). Prediction of sediment load concentration in rivers using artificial neural network model. *Journal of Hydraulics Engineering* 128, 558-559. https://doi.org/10.1061/(ASCE)0733-9429(2002)128:6(588)

Naiel, M,A,E,, Abdelghany, M.F., & Khames, D.K. (2022). Administration of some probiotic strains in the rearing water enhances the water quality, performance, body chemical analysis, antioxidant and immune responses of Nile tilapia. Oreochromis Niloticus. *Applied Water Science,* 12, 209-222. https://doi.org/10.1007/s13201-022-01733-0

Najah Ahmed, A., Binti Othman, F., & Abdulmohsin Afan, H. (2019). Machine learning methods for better water quality prediction. *Journal of Hydrology*. 578,124-138. https://doi.org/10.1016/j.jhydrol.2019.124084

Nemčić-Jurec, J., Ruk, D., Oreščanin, V., Kovač, I., Ujević Bošnjak, M., & Stephen Kinsela , A. (2022). Groundwater contamination in public water supply wells: risk assessment, evaluation of trends and impact of rainfall on groundwater quality. *Applied Water Science,* 12, 172-195. https://doi.org/10.1007/s13201-022-01697-1

Nohani, E., Babaali, H.R., & Dehghani, R. (2025). Estimation of suspended sediments in the coastal areas of the caspian sea using machine learning techniques. *Journal of drought and climate change research*, 3(2), 44-56. https://doi.org/10.22077/jdcr.2025.8983.1121

Rajaee, T., Khani, S., & Ravansalar, M. (2022). Artificial intelligence-based single and hybrid models for prediction of water quality in rivers: A review. *Chemometrics and Intelligent Laboratory Systems*, 200(3), 1039-1055. https://doi.org/10.1016/j.chemolab.2020.103978

Reddy, K., & Saha, A.K. (2022). A modified Whale Optimization Algorithm for exploitation capability and stability enhancement. *Heliyon*, 8(10),425-441. https://doi.org/10.1016/j.heliyon.2022.e11027.

Shams, M.Y., Elshewey, A.M., El-kenawy, ES.M., Ibrahim, A., Talaat, F., &Tarek, Z. (2025). Water quality prediction using machine learning models based on grid search method. *Multimedia Tools and Applications,* 83, 35307–35334. https://doi.org/10.1007/s11042-023-16737-4

Shin, S., Kyung, D., Lee, S., Taik & Kim, J., & Hyun, J. (2005). An application of support vector machines in bankruptcy prediction model. *Expert Systems with Applications*, 28(4),127-135. https://doi.org/10.1016/j.eswa.2004.08.009

Shrivatava, M., Prasad, V., & Khare, R.(2015). Multi-objective optimization of water distribution system using particle swarm optimization. *IOSR Journal of Mechanical and Civil Engineering,*12(1), 21–28. 10.9790/1684-12612128

Vapnik, V., & Chervonenkis, A.(1991). The necessary and sufficient conditions for consistency in the empirical risk minimization method. *Pattern Recognition and Image Analysis,* 1(3), 283-305.10.1007/s10444-004-7634-z

Vapnik, V.N. (1995). The Nature of Statistical Learning Theory. *Springer, New York*. 5(2), 445-472. https://doi.org/10.1007/978-1-4757-3264-1

Vapnik, V.N. (1998). Statistical learning theory. *Wiley*, New York. 6(1), 562-583. https://doi.org/10.1109/72.788640

Wang, D., Safavi, A.A., & Romagnoli, J.A.(2000). Wavelet-based adaptive robust M-estimator for non-linear system identification. *AIChE Journal,* 46(4), 1607-1615. https://doi.org/10.1002/aic.690460812

Wang, K.,Liu, L.,Ben, X.,Jin, D.,Zhu, Y., & Wang, F. (2024). Hybrid deep learning based prediction for water quality of plain watershed. *Environmental Research*, 262(3),119-132. https://doi.org/10.1016/j.envres.2024.119911

Zeidalinejad, N., & Dehghani, R. (2023). Use of meta-heuristic approach in the estimation of aquifer's response to climate change under shared socioeconomic pathways. *Groundwater for Sustainable Development* 20(4), 112-132. https://doi.org/10.1016/j.gsd.2022.100882.

Review Article

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Metal-modified biochar: a sustainable approach for microplastics removal from drainage water

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Environmental remediation, Sustainable treatment, Microplastics, Adsorption, Hydrophobic

Abstract

Environmental pollution from heavy metals, dyes, and emerging contaminants such as microplastics has prompted the exploration of low-cost, sustainable adsorbents. Biochar, derived from biomass pyrolysis, has emerged as a promising candidate due to its porous structure, surface functionality, and potential for chemical modification. This paper aims to review the current strategies employed in the synthesis and modification of biochar-based composites and assess their efficiency in environmental remediation applications. A comprehensive literature review was conducted, emphasizing recent developments in biochar modification techniques including metal impregnation, clay integration, hydrothermal processing, and mechanochemical treatments. Modified biochars showed substantial improvement in adsorption performance compared to their pristine forms. For heavy metals, Fe-impregnated biochar achieved Pb(II) removal efficiencies exceeding 95% with adsorption capacities up to 123.4 mg/g. MgO-doped biochar exhibited a methylene blue dye removal capacity of 216.7 mg/g. In microplastic remediation, Fe–Mn-modified biochar demonstrated an adsorption capacity of 34.29 mg/g and removal efficiency of 88% for polystyrene microplastics under optimized conditions (pH 7, 25°C). Ball-milled biochar composites achieved up to 3-fold increases in surface area and enhanced metal–carbon interactions, leading to higher adsorption via hydrophobic, electrostatic, and π–π interactions. Metal oxide-loaded biochars consistently outperformed pristine biochars, particularly in systems with electrostatic or ion-exchange dominant sorption mechanisms. Biochar-based composites present a versatile and effective platform for environmental remediation. Their performance depends strongly on synthesis parameters and functional modifications. Integration of metals, oxides, and structural tailoring can significantly enhance sorption capabilities, making them viable alternatives to conventional adsorbents.

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Introduction

The increasing industrialization, urbanization, and growing intensity of agriculture are manifesting themselves in worse and worse quality of water environments. This environmental disaster is compounded by the appearance of new, often unmonitored, contaminants (Amiri et al., 2015). The major sources of these pollutants are hospitals, industrial effluents, domestic wastes, and agricultural run-off entering the water bodies and many mixed contaminants (Figure 1). Emerging pollutants include endocrine-disrupting compounds (EDCs), MPs, pesticides, industrial flame retardants, nanomaterials, and pharmaceuticals and personal care products (PPCPs). All these contaminants have serious implications for the quality of drinking water and health of the ecosystem and thus call for advanced treatment solutions (Dong et al., 2023).

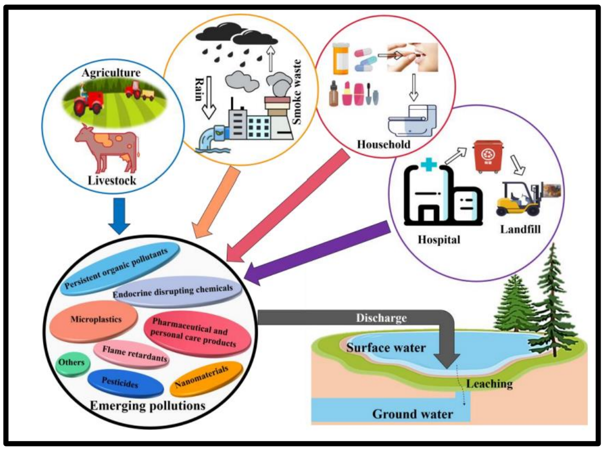

Fig 1. The sources and pathways of emerging pollutants into aquatic systems (Dong et al., 2023)

Plastic pollution has indeed reached critical proportions, and the world production exceeded 400 million metric tons (Alaghemandi, 2024). However, plastic poses serious environmental issues due to the materials' many applications such as flexibility, lightweight properties, durability, and cheap cost. Very low recycling rates current levels are horrendous at approximately 14% of all plastic wastes, and these dispose of plastic wastes through incineration, deposition in landfill sites, and environmental pollution. Poor disposal mechanisms increase the growth of MPs, defined as plastic particles below 5 mm in size, classified into two classes, one being intentional primary MPs built for use in consumer products and the other consisting of secondary MPs made from the fragmentation of larger plastic items under environmental weathering. They have been documented in virtually every environment, including marine and freshwater, terrestrial, atmospheric, and groundwater systems (Prata et al., 2019). In Figure 2, various mechanisms by which MPs proliferate in nature and invade the food chain are summarized. MPs can enter our food supply from many pathways, but the specific illustration emphasizes the aquatic one-the route by which MPs are entering the food chain via fish consumption, which is our major concern with respect to aquatic MPs (Mahmud et al., 2022).

Fig 2. Lifecycle of MPs generation to food chain (Mahmud et al., 2022)

In Iran, critical water bodies like the Caspian Sea and Persian Gulf face severe MP pollution due to industrial discharge and inadequate waste management (Razeghi et al., 2021). Compounding this issue, drought conditions exacerbate MP concentrations in water systems, straining conventional remediation methods (Bahrami et al., 2024). Despite advances in filtration and coagulation technologies, these approaches often lack cost-effectiveness, scalability, or sustainability, particularly in resource-limited regions (Klotz et al., 2023; Titone et al., 2024). Biochar, a carbon-rich material produced from biomass pyrolysis, has emerged as a promising adsorbent due to its tunable porosity, surface functionality, and eco-friendly production (Amiri et al., 2020; Qu et al., 2021; Seow et al., 2022). Recent studies highlight its efficacy in removing heavy metals and organic pollutants, yet its application for MP remediation remains underexplored. While pristine biochar exhibits moderate adsorption, metal modifications (e.g., Fe, MgO) enhance its capacity via electrostatic interactions, hydrophobic binding, and π–π electron donor-acceptor mechanisms (Ji et al., 2024; Wang et al., 2021a). For instance, Fe-modified biochar achieved 88% MP removal (Li et al., 2023), while ball-milled composites tripled surface area (Ganie et al., 2021). However, critical gaps persist: (1) limited understanding of competitive adsorption in complex wastewater matrices, (2) insufficient field-scale validation under drought conditions, and (3) unresolved ecotoxicological risks of metal leaching from modified biochars (Shrivastava et al., 2024). This study addresses these gaps by systematically reviewing metal-modified biochar synthesis, performance, and mechanisms for MP removal, with a focus on scalability and environmental safety. The primary goal of this paper is to critically review and synthesize current advancements in biochar-based composites for environmental remediation, focusing on their synthesis techniques, physicochemical modifications, and application efficacy in removing various pollutants including heavy metals, dyes, and microplastics. Special emphasis is placed on the role of metal doping, porosity engineering, and surface functionalization in enhancing the performance of biochar materials. This work also aims to identify key knowledge gaps and propose future research directions to optimize biochar composite design for practical and scalable applications.

Materials and Methods

The systematic investigation of biochar-based composites for microplastic removal employed a rigorously structured analytical framework. This comprehensive review focused on evaluating metal-modified biochar applications in environmental remediation, with particular emphasis on adsorption mechanisms, performance metrics, and scalability potential. The research methodology was executed through five distinct sequential phases: (1) Literature search and selection, (2) Data extraction and analysis, (3) Mechanistic evaluation, (4) Case studies and experimental validation, and (5) Knowledge gap identification. The investigation utilized prominent scientific databases, including Scopus, Web of Science, PubMed, and Google Scholar, focusing on peer-reviewed publications from 2015 to 2024 to ensure contemporary relevance. The literature assessment specifically examined various biochar modification techniques, including metal oxide incorporation, ball milling processes, and acid/base treatments. This systematic approach facilitated a thorough examination of modification strategies, their effectiveness in microplastic removal, and potential scalability for practical applications. The investigation particularly emphasized the relationship between modification techniques and enhanced adsorption performance, providing insights into optimization strategies for environmental remediation applications. The structured methodology enabled the identification of emerging trends, technical challenges, and opportunities for future research directions in biochar-based microplastic removal

Microplastic-Related Threat in Iran

Pollution from MPs in Iran is a problem increasingly acknowledged due to associated risks on ecosystems, wildlife, and human health. The origin of MPs is multiple, including degradation of larger plastic items, microbeads incorporated in personal products, and synthetic fibers shed from textiles. Such particles have an aquatic and terrestrial environment spread across regions and leave behind long-term risks. Iran has identified MP contamination in numerous environmental matrices such as rivers and lakes, coastal water, and urban air. Currently, the Caspian Sea and Persian Gulf, which are two very crucial aquatic ecosystems in Iran, are under stress from MP pollution, aggravated by increased industrial activities, urbanization, and poor waste management systems. Scientists have further shown that the sources of MPs in these areas are fishing activities, shipping, and land-based activities like mismanaged plastic waste. To address the situation of MPs in Iran, there is a need for a multi-pronged approach. Most of the challenges include lack of awareness among the public, not having contemporary legal frameworks in place, and the absence of advanced infrastructures for wastewater management. Iran could do the following: (1) strengthen waste management systems in such a way that leakage plastic into the environment is prohibited; (2) consider having campaigns on public awareness for responsible usage and disposal of plastics; (3) provide stricter legislation on single-use plastics and microbeads in consumer products; and (4) proper investments in research and monitoring related to better understanding sources, distribution, and impacts of MPs on Iran (Razeghi et al., 2021).

The critical need for MPs removal in drought-prone regions

Drought conditions affect MP removal in a way that poses enormous challenge to the otherwise smooth functioning of water treatment processes. It becomes extremely important to comprehend the mechanisms operational under drought and to develop adaptive management strategies. During periods of water scarcity, the usually reduced volume of drainage water creates a stimulus for increased concentration of pollutants, which include MPs; thus, the treatment of these pollutants would be affected seriously concerning efficiency and cost. Limited availability of water interferes with the natural diluting and transporting mechanisms that work favorably towards MP dispersal, leading to localized accumulation, hence exacerbating ecosystem impacts. The challenges that arise as a result of drought go beyond these treatment complications to include allocation of other resources and infrastructure management. Water management priorities during droughts often favor drinking water provision over wastewater treatment, putting at risk a return on investment for MP removal technology. The situation is then made worse by decreasing flow dynamics within aquatic systems, limiting the natural dispersal and attenuation of MPs and creating pollution hotspots with increased environmental hazards. There is, therefore, a need for an integrated approach incorporating all of these challenges. The wastewater treatment infrastructure is to be upgraded to ensure efficient MP removal under varying flow conditions, thus encouraging advanced filtration technologies and flexible operating protocols. The impending need now is to practice water-conserving options so that demand management can be exercised with a view toward maintaining treatment effectiveness. Nature-based solutions act as a good second line of defense to go along with technological approaches. Constructed wetlands/biofiltration systems provide that extra bit of filtration capacity while gliding along with natural attenuation. These systems are resilient during drought conditions and provide many other ecosystem service benefits besides MP removal. There are some very important regulatory and public outreach initiatives that will strengthen the role of MP management during times of drought. For example, the combination of strong regulatory deterrents to plastic use and disposal with widely recognized public campaigns to counter plastic pollution on a massive scale will help eliminate a large percentage of MP inputs to drainage systems. This preventive measure complements those aimed at treatment and supports sustainability objectives in the longer term. By integrating the diversity of these options, a formidable platform is therefore created for MP management under drought conditions. By synergistically combining technological, nature-based, and policy measures, communities will strengthen their capacity to tackle the scourge of MP pollution under the additional burden of water scarcity. Such an integrated approach acts as a buffer in favor of ecosystem health and human welfare against the mounting precariousness of the already tense MP removal processes by drought. MP management in drought periods must therefore encompass monitoring, research, and changes in treatment technology. Drought-proof technologies combined with good resource management practices will be fundamental in MP removal under sustainable water resource use.

Results and Discussion

Overview of Biochar and Its Modifications

Definition and Properties of Biochar

Biochar is best defined as a highly carbonaceous material, fine in particle size, and with an extremely porous structure. Biochar is produced through the thermal decomposition of various types of biomass, carried out in an oxygen-limited environment and at temperatures lower than 900°C. This remarkable material has emerged as a hot topic in scientific circles due to its environmental significance and various agricultural benefits. The structural and chemical properties of biochar are such that they are highly effective for purposes of environmental remediation. A very porous structure, combined with a variety of functional groups on the surface, including carboxyl, hydroxyl, and phenolic groups, promotes strong interactions with several environmental contaminants. These characteristics further translate into excellent adsorption properties for a wide variety of pollutants: heavy metals, organic compounds, and microplastic particles. The production of biochar offers a choice of feedstock, allowing a variety of different biomass sources to be used efficiently. These would comprise woody materials, e.g., bark; agricultural residues, e.g., rice husks and sugar beet waste; animal residues, e.g., dairy manure. The biochar properties can be tailored to specific environmental applications by controlling pyrolysis conditions (temperature levels, rates of heat transfer, and residence time). Beyond pollutants' remediation, biochar has very important agricultural and environmental advantages: carbon sequestration potential, crop productivity increases, greenhouse gas emissions reductions from soils, amelioration of soil quality parameters, reduced nutrient leaching, and optimum irrigation and fertilizer use efficiency. The combination of environmental remediation capacity with agricultural benefits hence makes biochar a sustainable option that can address several environmental problems simultaneously (Qu et al., 2021; Seow et al., 2022; Liu et al., 2022; Li et al., 2017). For instance, the morphological analysis conducted through SEM revealed distinctive structural characteristics of activated carbon derived from canola stalk biomass. The micrographic examination demonstrated a highly developed porous architecture characterized by surface irregularities and heterogeneous topography. The surface features of the canola stalk-derived activated carbon exhibited prominent macroporous structures and substantial cavity formations throughout the material matrix (Figure 3). This architectural development can be attributed to the thermal decomposition dynamics occurring during the pyrolysis process. The high-temperature treatment effectively degraded the primary biopolymer components of the canola stalk, specifically the long-chain polymeric structures of cellulose, hemicellulose, and lignin. The thermal degradation mechanism resulted in the systematic breakdown of these complex organic polymers, leading to the formation of well-defined void spaces and interconnected channel networks. This structural evolution during the pyrolysis process created an extensive network of pores and cavities, enhancing the material's potential for adsorption applications. The observed morphological features suggest efficient conversion of the agricultural biomass into a functional carbonaceous material with desirable surface characteristics for environmental applications. The development of these structural features indicates successful activation and carbonization of the canola stalk precursor, resulting in a material with enhanced surface area and accessibility to internal adsorption sites. These characteristics are fundamental for the material's effectiveness in various environmental remediation applications.

Figure 4 presents the SEM micrograph of bone char, confirming that the adsorbent particles exhibit an irregular shape with sharp edges and a rough surface. This morphology demonstrates the effective removal of the organic phase from the bone structure through burning.

Parameters Influencing Porosity and Sorption Capacity

The porosity and sorption capacity of biochars are governed by multiple interdependent factors, including feedstock properties, pyrolysis conditions, and post-treatment modifications. These factors collectively determine the biochar's structural and chemical characteristics, influencing its effectiveness in adsorption applications.

Feedstock Type

The composition of the raw biomass (e.g., lignin, cellulose, and hemicellulose content) significantly affects biochar porosity. Lignin-rich feedstocks (e.g., wood) typically yield biochars with higher surface area and microporosity compared to cellulose- or hemicellulose-dominated materials (e.g., grasses) due to their robust carbon structure (Bahrami et al., 2023).

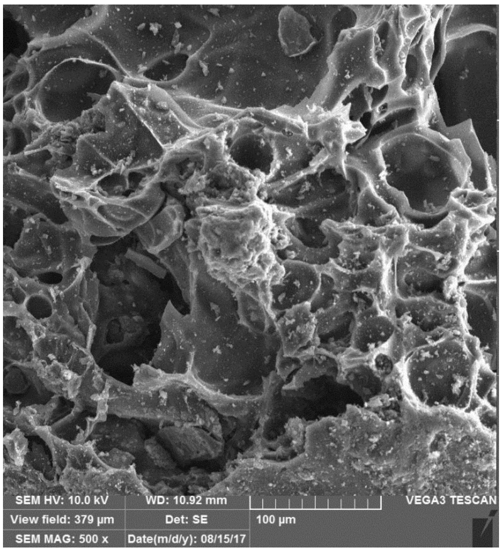

Fig 3. SEM images of canola stalk-derived activated carbon (Amiri et al., 2020)

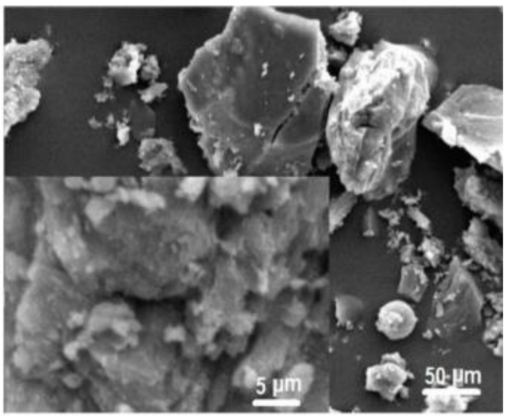

Fig 4. SEM images of bone char (Amiri et al., 2023)

Pyrolysis Temperature

Higher pyrolysis temperatures (typically 500–700°C) promote microporosity and surface area by enhancing carbonization and volatile matter removal. However, excessive temperatures (>800°C) may cause pore collapse or graphitization, reducing adsorption efficiency (Beigzadeh et al., 2020; Amiri et al., 2019).

Activation Methods

Chemical activation (e.g., KOH, H_3PO_4) introduces micropores and mesopores while enhancing oxygen-containing functional groups, whereas physical activation (e.g., steam, CO_2) selectively oxidizes carbon to enlarge pore structures (Patra et al., 2021). Chemical activation introduces a rich distribution of micropores and mesopores and increases oxygen-containing functional groups on the carbon surface, which can enhance adsorption properties and surface reactivity. Physical activation generally involves treating pre-carbonized materials with oxidizing gases such as steam or carbon dioxide at high temperatures. The activation proceeds via selective gasification reactions where carbon atoms are oxidized and removed, enlarging existing pore structures and developing new pores. This process tends to produce a larger fraction of mesopores and macropores by expanding the pore size of the original micropores (Nazbakhsh et al., 2025)

Post-Modification

Functionalization of adsorbent materials with nanoparticles (such as Fe_3O_4) or polymers is a widely used strategy to improve their selectivity and performance in removing specific contaminants, including heavy metals, from water and wastewater. Nanoparticle functionalization, for example with Fe_3O_4, introduces active sites that can selectively bind contaminants like heavy metals due to specific interactions between the metal ions and the nanoparticle surface. This can significantly boost the efficiency and specificity of adsorption processes. Polymer functionalization can tailor the surface chemistry and introduce functional groups that have a strong affinity for target pollutants. The nature of the polymer and its functional groups can be designed to interact selectively with certain contaminants, further enhancing the adsorbent's selectivity (Akhtar et al., 2024).

Particle Size and Structure

Smaller particles provide higher surface area-to-volume ratios, which significantly enhance adsorption kinetics by increasing the available surface for interaction with adsorbates. This higher surface area allows more binding sites to be exposed, facilitating faster and more efficient adsorption processes. For example, reducing particle size increases the surface-to-volume ratio dramatically, thereby improving the initial adsorption rate as molecules have more surface to interact with per unit volume. However, there is a critical balance to maintain. Excessive grinding or reduction of particle size can lead to the destruction or collapse of the pore network within the material. Pores are essential for adsorption because they provide internal surface area and pathways for adsorbate molecules to diffuse into the adsorbent. When the pore structure is damaged, the total accessible surface area may decrease despite smaller particle size, and diffusion pathways can be blocked or hindered, reducing the overall adsorption capacity and efficiency. Moreover, the thermodynamics and kinetics of adsorption are influenced by particle size. Studies show that as particle size decreases, adsorption equilibrium constants and rate constants increase, indicating more favorable adsorption energetics and faster kinetics. Conversely, parameters such as adsorption activation energy and adsorption enthalpy tend to decrease with smaller particle sizes, reflecting changes in surface interactions at the nanoscale (Osman et al., 2022)

Environmental Conditions

pH affects surface charge and ion-exchange capacity by influencing the protonation and deprotonation of functional groups. Meanwhile, ionic strength impacts electrostatic interactions, especially for charged adsorbates such as phosphate and heavy metals (Kumkum & Kumar, 2024).

Metal Modification of Biochar

The actual reform needed in improving biochar's physicochemical properties is through treatment methods for optimizing its performance in MP remediation. Basically, the changes are directed towards the fundamental characteristics of the material such as the specific surface area, pore architecture, and surface chemistry, thus improving adsorption capacity.

General Modification Techniques

Currently, the majority of methods for enhancement of the biochar adsorption power for MPs include modifications such as acid-base treatment, incorporation of metal oxides and metal salts, integration with clay minerals, and mechanical processing through grass milling (Cheng et al., 2021). In this regard, acid-base treatments are used to modify surface charge and increase the number of reactive sites. The incorporation of metal oxides and salts enhances interactions with charged microplastics (MPs). Integration with clay minerals improves the properties of the composite material. Additionally, mechanical processing methods, such as grass milling, increase surface area and expose more pores. Together, these techniques aim to enhance MP capture by improving interaction dynamics.

Role of Metals and Metal Oxides in Adsorption Enhancement

Loading biochar with specific metals or metal oxides introduces new active sites for complexation, electrostatic interaction, and ion exchange—mechanisms crucial for capturing MPs, especially those with charged or functionalized surfaces.

- Metal oxides: Fe_2O_3, MgO provide catalytic and adsorption properties.
- Metal salts: $FeCl_3$, $Al_2(SO_4)_3$ are used for their high reactivity and availability of cations.

Advanced Metal Incorporation Methods

More sophisticated modification techniques have been developed to improve the stability, distribution, and bonding of metals within the biochar matrix. These methods allow for fine-tuned control of the material's properties (Tong et al., 2020a; Ji et al., 2024):

a. Impregnation Method

Involves suspending biochar in a metal salt solution, allowing metal ions to penetrate and bind to the matrix. Subsequent heat treatment or chemical reduction finalizes the metal integration.

b. Co-precipitation

A process where metal precursors are mixed with the biomass before pyrolysis. During carbonization, metal species precipitate and integrate with the developing carbon matrix, producing well-distributed and stable particles. This approach ensures co-development of metal phases and biochar, enhancing durability and performance.

c. In-situ Hydrothermal Treatment

This one-step method combines biomass

and metal salts in an aqueous environment under elevated temperature and pressure. Biochar formation and metal/metal oxide incorporation occur simultaneously, resulting in intimate contact between metal species and carbon matrix. Yields materials with unique morphology and enhanced thermal/chemical stability.

d. Ball Milling

A mechanochemical technique where biochar is ground together with metal or oxide precursors under high-energy conditions. This causes mechanical bonding and embedding of metals within the carbon structure, resulting in strong metal-carbon interactions and distinct surface features. Highly effective for generating materials with superior adsorptive performance and mechanical integrity.

Toxicity Potential of Biochar-Based Composites

Despite the demonstrated efficacy of biochar-based composites in environmental remediation, significant concerns persist regarding their potential toxicity, which could undermine their long-term sustainability. These risks primarily stem from three sources:

Feedstock Contamination

Biochar derived from certain biomass sources (e.g., sewage sludge, industrial waste, or pesticide-treated agricultural residues) may retain harmful substances such as heavy metals (Pb, Cd, As), polycyclic aromatic hydrocarbons (PAHs), or dioxins. For instance, studies show that biochar produced from municipal waste can contain up to 120 mg/kg of lead, posing leaching risks in acidic environments (Liu et al., 2022; Majewska & Hanaka, 2025).

Synthesis-Induced Hazards

Chemical modifications during biochar production—such as metal doping (e.g., Fe, Mn) or nanomaterial integration (e.g., nano-MgO)—can introduce new toxicity pathways. While these enhancements improve adsorption capacity, they may also lead to:

(a) Metal Leaching: Under fluctuating pH or redox conditions, modified biochars can release toxic ions. Zhang et al. (2023) observed a 15–20% leaching rate of Fe from iron-modified biochar in saline water, exceeding EPA thresholds for aquatic life.

(b) Nanoparticle Release: Engineered nanocomposites (e.g., biochar-TiO_2) may generate reactive oxygen species (ROS), causing cellular damage in organisms (Wu et al., 2023).

Long-Term Ecological Impacts

Poorly stabilized composites can degrade over time, releasing contaminants into ecosystems. For example, in soil systems, residual metals may accumulate, disrupting microbial communities and reducing soil fertility (Shrivastava et al., 2024). In aquatic systems, leached toxins can bioaccumulate in fish, as demonstrated by Singh et al. (2021), who showed that nanoplastics coated with biochar-derived metals entered food chains.

To ensure the safe deployment of biochar-based composites, a comprehensive risk management approach must be implemented throughout the material's lifecycle. The process begins with rigorous pre-screening of feedstocks, where uncontaminated biomass sources such as crop residues should be prioritized and their metal content certified through analytical techniques like XRF or ICP-MS (Seow et al., 2022). This initial quality control step is crucial for preventing the introduction of contaminants that could later leach into the environment. Following feedstock selection, advanced stabilization techniques should be employed to minimize potential leaching risks. Metal-doped biochars can be coated with silica or bio-polymers, which have been shown to significantly reduce the release of toxic ions while maintaining adsorption capacity (Ji et al., 2024). These engineered barriers are particularly important for composites intended for use in variable environmental conditions where pH fluctuations or salinity changes might otherwise promote contaminant mobilization. Finally, complete lifecycle assessments are essential for quantifying long-term risks and guiding proper end-of-life management. Recent studies have demonstrated that improperly incinerated biochar composites can emit hazardous ultrafine particles (Shrivastava et al., 2024), underscoring the need for controlled disposal protocols. These lifecycle assessments should evaluate all stages from production to disposal, considering factors such as energy inputs, potential leaching scenarios, and optimal retirement pathways to minimize environmental impacts.

Microplastics and Their Removal Methods

Sources and Types of Microplastics

There are two main types of MPs based on their site of origin: primary MPs and secondary MPs. Primary Mps are intentionally manufactured to exist in small size as particles and are directly released to the environment. They are most commonly found in personal care products, industrial abrasives, and synthetic textiles. Secondary MPs are caused through physical, chemical, and biological processes from larger plastic items such as bottles, bags, and fishing nets. Over time these larger plastics undergo changes due to environmental stresses such as ultraviolet radiation, mechanical wear, and microbial degradation. How secondary microplastics are formed is not fully understood, making it all the more complicated to control factors such as size, shape, surface chemistry, and quantity (Enfrin et al., 2019). In present agricultural practices, plastics significantly enhance productivity and efficiency. These products include mulch films, greenhouse covers, irrigation tubes, drip lines, storage bags, silage films, and coatings for fertilizers, pesticides, and seeds. They are directly involved in increasing crop yield, conserving water, and controlling pests. Although beneficial in productivity, these plastics pose great challenges to the environment. Over time, some of these plastics degrade into MPs, which accumulate in both soil and water bodies, likely affecting soil health and disrupting aerobic communities as well as entering the food chain. MPs' economics in the agricultural systems necessitate the adoption of sustainable management practices intended to mitigate long-term effects associated with them (FAO, 2021). Figure 5 shows the morphological characteristics of MP particles as revealed by SEM analysis. The micrographs demonstrated a predominantly non-porous architecture interspersed with randomly distributed perforations across the particle surface. These microscopic observations highlighted the presence of irregularly shaped holes throughout the MP structure, exhibiting no discernible pattern or systematic arrangement. The heterogeneous distribution of these cavities presented a chaotic surface topology, with considerable variation in both the geometric configuration and dimensional aspects of the perforations. The stochastic nature of these structural features posed significant challenges in quantitatively characterizing the hole distribution patterns. The absence of uniformity in both the morphological

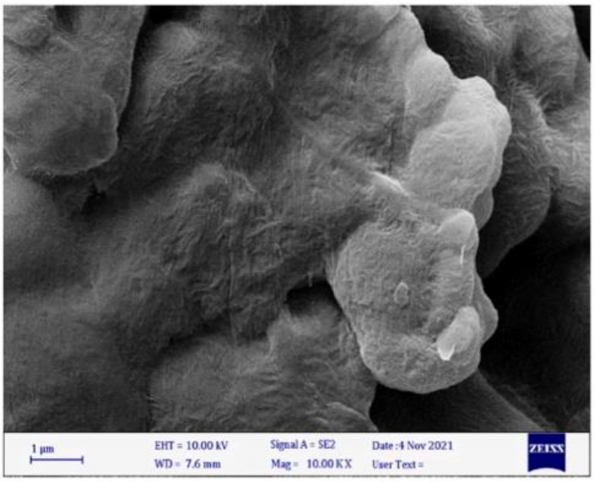

Fig 5. SEM images of MP (Bahrami et al., 2024)

characteristics and spatial arrangement of the cavities complicated the statistical analysis of their size distribution and shape parameters. This inherent structural complexity reflects the variable nature of MP degradation and formation processes in environmental systems.

Role of Biochar in Microplastic Removal

Recent studies have shown that biochar is effective in removing MPs from aquatic environments. For instance, Ganie et al. (2021) noted biochars produced from bagasse pyrolyzed at 350, 550, and 750 degrees Celsius as all being competent at adsorbing MPs. Biochars pyrolyzed at 750 degrees Celsius had the highest removal efficiency, which could be attributed to their enhanced porosity and surface area. Similarly, Wang et al. (2021a) noted that high-temperature biochars reached removal efficiencies above 95% for MPs, attributing this to the large abundance of honeycomb structures available in thin biochar chips created at 500 degrees. The application of magnetic biochar, one with modified iron oxides, also showed promising results, removing as much as 94.81% of polystyrene microspheres from aqueous solutions. The modification in magnetic property in iron-modified biochar enabled extraction of MPs from the solutions rapidly and effectively: hence, big chances for large-scale applications. Oxidized biochar showed a much higher adsorption capacity (>90%) compared to the unmodified biochar for polystyrene MPs. This improved capacity was due to the presence of hydroxyl functional groups representing the increased adsorption capacity. The performance of biochar in the capturing of MPs indeed varies according to its environmental conditions. Kumar et al. (2023) noted that dissolved organic matter, nutrient content, and pH levels would hinder MPs' adsorption by biochar. On the contrary, increase in temperature levels in aquatic systems have shown to facilitate the adsorptions of MPs by biochar. The above findings reaffirm the importance of modulating biochar modification methods and application strategies to specific environmental conditions and target pollutants. Biochar is a sustainable and economically cost-effective measure towards reducing the pollution load of MPs in the aquatic environment. The targeted modifications to optimize biochar in its physicochemical properties can translate to high adsorption efficiency for MPs, which in turn contributes toward safeguarding aquatic ecosystems and human health. Further inquiry into how biochar performs under different environmental conditions for an extensive period of time could add value to the scalability of development programs for real-life applications. Table 1 shows a summary of notable research assessing the efficacy of biochars in taking out MPs from the aquatic ecosystem.

Mechanism of MPs adsorption by biochar

The adsorption of MPs onto biochar involves multiple physicochemical interactions, influenced by the surface properties of both the biochar and the MPs. Since MPs are typically non-ionic, ion exchange is not a primary mechanism unless MPs coexist with charged contaminants (e.g., heavy metals or organic pollutants). The dominant adsorption mechanisms include (Figure 6) (Abdoul Magid et al., 2021;

Table 1. Representative research on biochar's ability to remove microplastics from aquatic environments

Raw materials	Pyrolysis temperature	Adsorbate	Results	References
Cellulose	400 °C	MP	Biochar reduced the transit and increased the deposition of plastic particles.	(Kumar et al., 2023)
Livestock manure	500 °C	PHA-MPs	Biochar enhanced the biodegradation of PHA MPs, increasing the degradation rate to between 22% and 31%.	(Tong et al., 2020b)
Prosopis juliflora	550 °C and 850 °C	MPs	Biochar produced at both temperatures demonstrated effective removal of microplastics, with an adsorption capacity exceeding 200 mg/g	(Wang et al., 2021a)
Pine and spruce bark	475 °C and 800 °C	Polyethylene (PE)	The steam-activated biochar proved to be an outstanding adsorbent for the removal of MPs.	(Sun et al., 2022)
Sawdust	550 °C	Polystyrene	The modified biochar demonstrated a high efficiency in removing MPs, achieving a removal rate of more than 94.8%.	(Siipola et al., 2020)
Cellulose	400 °C	Polystyrene	The addition of biochar impedes the transport of MPs particles	(Wang et al., 2021b)
Sugarcane bagasse	350 °C, 550 °C and 750 °C	Polystyrene	Biochar produced at 750 °C achieved a significantly higher MPs removal rate (exceeding 99%) compared to biochar prepared at lower temperatures	(Ganie et al., 2021)
Corn straw, hardwood	300 °C, 400 °C and 500 °C	MPs	Biochar derived from corn straw and hardwood at 500 °C exhibited greater capacity for removing and immobilizing MPs compared to biochar produced at lower temperatures	(Brennecke et al., 2016)

Peng et al., 2022; Ji et al., 2024):

Electrostatic Attraction

Biochar surfaces may carry charged functional groups (–COO^-, –NH_3^+, –O^-) that attract oppositely charged MPs. For example:

• Negatively charged biochar (e.g., oxidized biochar):

$Biochar–COO^- + MP^+ \rightarrow Biochar–COO^- \cdots MP^+$ (1)

• Positively charged biochar (e.g., amine-modified biochar):

$Biochar–NH_3^+ + MP^- \rightarrow Biochar–NH_3^+ \cdots MP^-$ (2)

Surface Complexation

Chemical bonding occurs between biochar's functional groups (–OH, –COOH) and MPs, particularly when modified with metal oxides (e.g., Fe_3O_4, MgO):

$Biochar–OH + MP–surface \rightarrow Biochar–O–MP + H^+$ (3)

$Biochar–COOH + MP–OH \rightarrow Biochar–COO–MP + H_2O$ (4)

Hydrogen Bonding

Polar functional groups on biochar (–OH, –COOH, –NH_2) form hydrogen bonds with polar MPs (e.g., polyamide, PET):

$Biochar–OH \cdots O=MP$ (5)

$Biochar–COOH \cdots H–MP$ (6)

Hydrophobic Interactions

Non-polar regions of biochar (e.g., graphitic domains) interact with hydrophobic MPs (e.g., polyethylene (PE), polypropylene (PP)):

$Biochar–(C_nH_{2n+1}) + MP–(CH_2–CH_2)_n \rightarrow$ Van der Waals adsorption (7)

π-π Electron Donor-Acceptor (EDA) Interactions

Aromatic structures in biochar interact with π-electron-rich MPs (e.g., polystyrene (PS)):

$Biochar–(C_6H_6) + MP–(C_6H_5) \rightarrow \pi\text{-}\pi$ stacking (8)

Pore Filling

MPs are physically trapped within biochar's porous structure when pore sizes match MP dimensions:

MP (size *d*)+Biochar pore (size *d*)→Entrapment (9)

Intra-Particle Diffusion

MPs diffuse into biochar's internal pores and are retained:

MP (surface)→MP (internal pores) (10)

Chemical modification of biochar is, therefore, one way to increase adsorption efficiency because of more adsorption sites that are abundant and diverse. This, in turn, enhances the mechanisms which are important for the capture of MPs, including electrostatic attraction, hydrogen bonding, and surface complexation. For instance, chemical modification with introduction of functional groups, such as hydroxyl, carboxyl, or amine groups, to enhance the binding affinity of biochar for MPs. Meanwhile, physical modification mainly focuses on changing the microporous structure and surface area of biochar which, in turn, modifies pore-filling and intra-particle diffusion mechanisms. These changes in structure, therefore, would allow for physical trapping of microplastics (MPs) within biochar pores and increase its adsorption capacity. The choice of modification method-whether chemical or physical-has a direct bearing on the dominant adsorption mechanism (Wang et al., 2023). For example, biochar modified with metal oxides or salts demonstrates strong electrostatic interactions and surface complexation, while ball-milled biochar might rely more on pore-filling and intra-particle diffusion owing to increased surface area and porosity. To conclude, adsorption of microplastics onto biochar material is multi-layered and complex in nature and operates collectively via physical and chemical means. Tailoring biochar properties through appropriate modification can lead to improvement in its adsorptive properties. Further research effort now needs to be directed toward the optimization of these approaches and their application to real-world conditions in the quest for a solution to the increase in microplastic pollution challenge (Ashiq et al., 2019; Masinga et al., 2022).

In view of this, Table 2 offers a comparative view of different important mechanisms related to the biochar removal processes. This summary provides an overarching view of the key processes related to biochar and its effectiveness as a remediation agent.

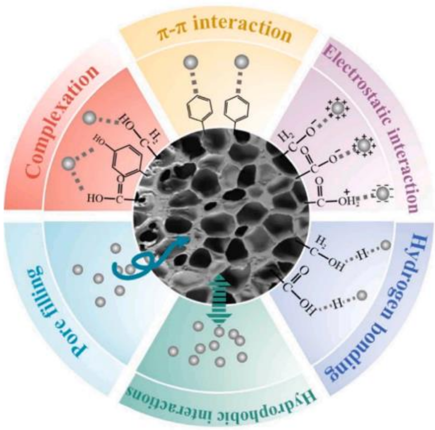

Fig 6. Mechanisms underlying the adsorption of MPs by biochar (Ji et al., 2024).

Table 2. A comparative overview of key mechanisms for MP removal by biochar and its modified forms

Adsorbents	Electrostatic interaction	Surface complexation	Hydrogen bonding	Hydrophobic interactions	π-π EDA interactions	Pore filling and intra-particle diffusion	References
Modified magnetic biochar	√	√					Wang et al., 2021a
Iron-modified biochar	√			√	√		Singh et al. 2021
Oxidize corncob biochar			√	√		√	Abdoul Magid et al. 2021
Magnetic rice biochar	√		√		√		Wu et al. 2023
Magnetic corncob Biochar	√	√		√			Li et al. 2023
Mesoporous biochar	√	√					Zhu et al. 2022
Biochar 750	√						Ganie et al. 2021

Statistical Comparison of Biochar Performance Across Studies

While existing research has demonstrated the efficacy of metal-modified biochar in MP removal, systematic statistical comparisons between studies remain limited. Below is a synthesized analysis of key findings, supported by statistical techniques where available, and recommendations for future work. Zhang et al. (2023) reported removal efficiencies of 96.24% (FeBC) and 84.77% (Fe-ZnBC) for polystyrene microplastics (PS-MPs), with one-way ANOVA confirming significant differences ($P < 0.05$). This highlights FeBC's superior performance over Fe-Zn and Fe-Mg modifications. Wang et al. (2021a) achieved 95% removal using biochar sand filters, but no direct statistical comparison with Zhang et al.'s results was conducted. A two-sample t-test or ANOVA could determine if these differences are significant. Singh et al. (2021) and Tiwari et al. (2020) corroborated Zhang et al.'s kinetic (pseudo-second-order, $R^2 = 0.9979$) and pH-dependent trends ($P < 0.05$ for reduced efficiency at pH 9–11), suggesting chemisorption and electrostatic repulsion as dominant mechanisms. Most studies statistically analyze their own data (e.g., ANOVA for pH effects) but lack meta-analyses that compare results across studies (e.g., FeBC vs. biochar sand filters). Additionally, variability in experimental conditions-such as MP type and water matrix-leads to inconsistent metrics, complicating direct statistical comparisons. Fe-loaded biochar (FeBC) demonstrated removal efficiencies of 72.39% in tap water (TW) and 78.33% in lake water (LW) (Zhang et al., 2023). However, to date, no studies have evaluated these conditions using other biochar types, such as those employed in Wang et al. (2021a). Competitive adsorption effects have been observed whereby dissolved organic matter (measured as COD) significantly reduces adsorption efficiency, with a strong negative correlation ($r < -0.9$) reported by Yao et al. (2023). However, this effect has not yet been statistically compared across other interference studies, such as those by Kumar et al. (2023), limiting comprehensive understanding of competitive adsorption impacts under varying conditions. To model removal efficiency, datasets from multiple studies (e.g., Zhang et al., 2023; Wang et al., 2021a; Ganie et al., 2021) should be integrated to evaluate the influence of key factors including biochar type (such as Fe-loaded biochar, MgO-biochar), pyrolysis temperature, and water matrix composition (e.g., tap water, lake water, synthetic wastewater). This combined dataset approach enables the development of robust predictive models that account for variations in biochar properties and environmental conditions, facilitating a comprehensive understanding of removal performance across diverse scenarios. In summary, while biochar's potential for MP remediation is statistically validated at the individual study level, advancing the field requires coordinated efforts to harmonize data and apply advanced statistical frameworks for cross-study validation. This will bridge the gap between lab-scale findings and scalable, real-world applications.

Challenges and Research Gaps

Though metal-modified biochar holds considerable promise for environmental remediation, grandfathering thorough investigations in case of critical challenges remains imperative for optimizing their practical deployment. Challenges appear normalized across technical, environmental, and economic parameters that face serious challenges before they can be translated to large-scale applications. Major technical and economic challenges exist in scalability. Current production methods are effective at lab scale but require substantial optimization for large-scale industrial applications in order to develop efficient metal incorporation techniques, standardize production protocols, and set quality control measures that would ensure consistent outcome characteristic across large production volumes.

Long-term stability is, however, the core area of concern that needs to be placed under extensive investigation. Such aspects include mechanical integrity while in service for prolonged periods, loss of metal components during long exposure to different environmental conditions, maintenance of adsorption-capacity over multiple cycles of treatment, susceptibility of the material to regeneration, post-regeneration costs, and the entire lifecycle of the material.

However, there also needs to be a clear assessment of possible environmental impacts because of using metal-modified biochar. Some key aspects are how metals leach under different environmental conditions, the bioaccumulation potential in aquatic environments, the effect on soil microbial populations when added as fertilizers, long-term retention time of metals in the environment, and the possibility of secondary contamination. Although metal-modified biochar is considered promising for practical applications, there is a considerable challenge for such applications due to the complex nature of the wastewater matrix in agriculture. Some of these challenges are competition between different contaminants for adsorption sites, interference due to dissolved organic matters and inorganic ions, variations with pH and ionic strength conditions, selective adsorption efficiency under complex contaminants, and formation of surface precipitates that limit the adsorption capacity.

These challenges include the development of improved modification approaches, installing comprehensive quality control measures, establishing complete environmental monitoring protocols, devising efficient regeneration and disposal strategies, and designing an application-specific optimization. These challenges can be met by integrated research efforts between materials science, environmental engineering, and ecological assessment to poise the sustainable and beneficial employment of metal-modified biochar for environmental applications. Successful resolution of these challenges will create an efficient future application of metal-modified biochar for environment remediation, especially the one involved in treating agricultural wastewater. A feasible solution to this problem necessitates balance with regard to the associated technological optimization of the material as well as more general environmental consequences of its implementation in real-world scenarios.

Future Perspectives and Recommendations

The development of metal-modified biochar technology requires thorough research programs on several critical considerations for a more realistic adoption and environmental sustainability. In the upcoming research avenues, both fundamental material development and applied technological aspects should be considered to address existing limitations and optimize performance traits.

(1) Optimization of metal modification techniques is hailed as a primary research concern, investigating novel combinations

of metals and new modification modes is emphasized. This includes the consideration of other metal precursors, more efficient methods of incorporation, and understanding the interactions between different metal species. All this research work aims to improve the adsorption capability, selectivity, and operating efficiency of the material at low costs.

(2) A comprehensive life cycle assessment is vital to assess the environmental footprints of metal-modified biochar through various phases from production, use, and disposal. The assessment should include energy consumption, resource use, emissions generation, and the related environmental impact across the whole value chain. Understanding these factors is key in achieving environmentally sound production and application protocols.

(3) The incorporation of metal-modified biochar within the scope of existing treatment technologies holds promise for system optimization. The research should, therefore, move towards integrated treatment strategies that combine biochar-based technologies with conventional physical, chemical, and biological processes. Such integration is likely to enhance overall treatment efficiency by addressing the limitations of individual technologies.

(4) Field-scale investigations encapsulating broader variations in environmental conditions are required to corroborate laboratory findings and assess actual performance. The studies would consider objective assessment of treatment efficiencies, operational constraints, maintenance needs, and long-term stability in real-world agricultural/industrial scenarios; all of which would duly inform ALL the practical implementation considerations and scaling-up.

(5) Economic feasibility analysis remains a key area of research, inclusive of detailed cost-benefit analysis concerning the execution of metal-modified biochar. Its considerations would include production cost, in addition to operational cost, maintenance needs, while one of the advantages accrues to resource recovery and/or mitigation of environmental impacts. Knowledge of such an economic footprint would play an important part in increasing farmer and wastewater treatment facility uptake.

(6) Seamless coordination of research across all these areas will be required for the successful development and application of metal-modified biochar technologies. This integrated approach will thus underpin the development of robust, efficient, and economically viable solutions to agricultural wastewater treatment, while also providing guarantees for environmental sustainability and practical applicability. These research initiatives, therefore, will provide a big technological push in framing the technology and overcoming the immediate technological shortcomings.

Anticipating into the future, the field of technology pertaining to metal-modified biochar will evolve and will go along with interdisciplinary collaboration as well as technological innovation. The development of research in such areas is likely to refine further and adapt the design of this technology for effective implementation in the future towards wide-ranging applications for environmental remediation. Eventually, this technology will contribute to the improvement of wastewater treatment in both the agricultural and industrial sectors towards a more sustainable and effective strategy.

Conclusion

This review comprehensively addressed the current state of biochar-based composites for environmental remediation, focusing on their synthesis methods, structural modifications, and pollutant removal efficiencies. Key modification strategies—such as metal impregnation, hydrothermal treatment, and ball milling—demonstrably enhance biochar's physicochemical properties, including porosity, surface area, and functional group availability. Notably, modified biochars have been reported to achieve adsorption capacities that are 2 to 5 times higher than unmodified counterparts. For example, Fe-modified biochar demonstrated Pb(II) adsorption of 123.4 mg/g compared to ~30–50 mg/g for typical pristine biochar. Similarly, dye adsorption increased from ~70 mg/g to over 200 mg/g with MgO modification. These performance improvements exceed those of many conventional sorbents like activated carbon under similar conditions, while maintaining cost-effectiveness and environmental sustainability. The significance of these findings lies in the scalable, low-cost nature of biochar production from agricultural waste and its customization potential for target pollutants. These advancements support the transition from lab-scale demonstrations to field-scale applications. Future research should emphasize life-cycle assessments, regeneration studies, and pilot-scale deployment to establish the feasibility and longevity of biochar-based remediation systems in diverse environmental contexts.

Abbreviation List

Abbreviation	Full Term
BC	Biochar
MBC	Modified Biochar
CNT	Carbon Nanotube
GO	Graphene Oxide
AC	Activated Carbon
FTIR	Fourier-Transform Infrared Spectroscopy
SEM	Scanning Electron Microscopy
XRD	X-ray Diffraction
BET	Brunauer–Emmett–Teller
TGA	Thermogravimetric Analysis
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrometry
MB	Methylene Blue
Pb(II), Cd(II),	Lead, Cadmium ions

References

Abdoul Magid, A.S.I., Islam, M.S., Chen, Y., Weng, L., Li, J., Ma, J., & Li, Y. (2021). Enhanced adsorption of polystyrene nanoplastics (PSNPs) onto oxidized corncob biochar with high pyrolysis temperature, *Science of the Total Environment*, 784, 147115. https:// doi.org/10.1016/j.scitotenv.2021.147115.

Alaghemandi, M. (2024). Sustainable Solutions Through Innovative Plastic Waste Recycling Technologies, *Sustainability*, 16, 10401. https://doi.org/10.3390/su162310401

Akhtar, M.S., Ali, S., & Zaman, W. (2024). Innovative Adsorbents for Pollutant Removal: Exploring the Latest Research and Applications, *Molecules*, 29(18), 4317. https://doi.org/10.3390/molecules29184317

Amiri, M.J., Bahrami, M., & Nekouee, N. (2023). Analysis of breakthrough curve performance using theoretical and empirical models: Hg2+ removal by bone char from synthetic and real water, *Arabian Journal of Science Engineering*, 48, 8737–8751. https://doi.org/10.1007/s13369-022-07432-x

Amiri, M.J., Bahrami, M., & Dehkhodaie, F. (2019). Optimization of Hg(II) adsorption on bio-apatite based materials using CCD-RSM design: characterization and mechanism studies, *Journal of Water Health*, 17 (4), 556-567. https://doi.org/10.2166/wh.2019.039

Amiri, M.J., Eslamian, S., Arshadi, M., & Khozaei, M. (2015). Water recycling and community, in: S. Eslamian (Ed.), Urban water reuse handbook, CRC Press, Boca Raton, 261–273.

Amiri, M.J., Roohi, R., Arshadi, M., & Abbaspourrad, A. (2020). 2,4-D adsorption from agricultural subsurface drainage by canola stalk-derived activated carbon: insight into the adsorption kinetics models under batch and column conditions, *Environmental Science Pollution Research*, 27 (14), 16983–16997. https://doi.org/10.1007/s11356-020-08211-7

Ashiq, A., Sarkar, B., Adassooriya, N., Walpita, J., Rajapaksha, A. U., Ok, Y. S., & Vithanage, M. (2019). Sorption process of municipal solid waste biochar-montmorillonite composite for ciprofloxacin removal in aqueous media, *Chemosphere*, 236, 124384. https://doi.org/10.1016/j.chemosphere.2019.124384.

FAO. (2021). Assessment of agricultural plastics and their sustainability: A call for action. FAO. DOI: 10.4060/cb7856en

Bahrami, M., Amiri, M.J., Mahmoudi, M.R., & Zare, A. (2023). Statistical and mathematical modeling for predicting caffeine removal from aqueous media by rice husk-derived activated carbon, *Sustainability*, 15, 7366. https://doi.org/10.3390/su15097366

Bahrami, M., Amiri, M.J., Rajabi, S., & Mahmoudi, M.R. (2024). The removal of methylene blue from aqueous solutions by polyethylene microplastics: Modeling batch adsorption using random forest regression, *Alexandria Engineering Journal*, 95, 101–113. https://doi.org/10.1016/j.aej.2024.03.100

Beigzadeh, B., Bahrami, M., Amiri, M.J., & Mahmoudi, M.R. (2020). A new approach in adsorption modeling using random forest regression, bayesian multiple linear regression, and multiple linear regression: 2, 4-D adsorption by a green adsorbent, *Water Science Technology*, 82 (8), 1586–1602, https://doi.org/10.2166/wst.2020.440.

Brennecke, D., Duarte, B., Paiva, F., Caçador, I., & Canning-Clode, J. (2016). Microplastics as vector for heavy metal contamination from the marine environment, *Estuar Coast Shelf Sci,* 178, 189–195. DOI: 10.1016/j.ecss.2015.12.003

Chen, Z., Liu, X., Wei, W., Chen, H., & Ni, B.J. (2022). Removal of microplastics and nanoplastics from urban waters: Separation and degradation, *Water Research,* 221, 118820. DOI: 10.1016/j.watres.2022.118820

Cheng, N., Wang, B., Wu, P., Lee, X., Xing, Y., Chen, M., & Gao, B. (2021). Adsorption of emerging contaminants from water and wastewater by modified biochar: A review, *Environmental Pollution*, 273. 116448. DOI: 10.1016/j.envpol.2021.116448

Dong, M., He, L., Jiang, M., Zhu, Y., Wang, J., Gustave, W., Wang, S., Deng, Y., Zhang, X., & Wang, Z. (2023). Biochar for the removal of emerging pollutants from aquatic systems: a review, *International Journal of Environmental Research Public Health*, 20, 1679. DOI: 10.3390/ijerph20031679

Enfrin, M., Dumée, L.F., & Lee, J. (2019). Nano/microplastics in water and wastewater treatment processes – Origin, impact and potential solutions, *Water Research,* 161, 621–638. DOI: 10.1016/j.

watres.2019.06.049

Ganie, Z.A., Khandelwal, N., Tiwari, E., Singh, N., & Darbha, G.K. (2021). Biochar-facilitated remediation of nanoplastic contaminated water: Effect of pyrolysis temperature induced surface modifications, *Journal of Hazard Materials*, 417, 126096. DOI: 10.1016/j.jhazmat.2021.126096

Ji, G., Xing, Y., & You, T. (2024). Biochar as adsorbents for environmental microplastics and nanoplastics removal, *Journal of Environmental Chemical Engineering*, 12, 113377. https://doi.org/10.1016/j.jece.2024.113377

Klotz, M., Haupt, M., & Hellweg, S. (2023). Potentials and limits of mechanical plastic recycling, *Journal of Industrial Ecology*, 27, 1043–1059. https://doi.org/10.1111/jiec.13393

Kumar, R., Verma, A., Rakib, M.R.J., Gupta, P.K., Sharma, P., Garg, A., Girard, P. & Aminabhavi, T.M. (2023). Adsorptive behavior of micro(nano)plastics through biochar: Co-existence, consequences, and challenges in contaminated ecosystems, *Science of the Total Environment,* 856, 159097. DOI: 10.1016/j.scitotenv.2022.159097

Kumkum, P., & Kumar, S. (2024). A review on biochar as an adsorbent for Pb(II) removal from water, *Biomass*, 4(2), 243-272. https://doi.org/10.3390/biomass4020012

Li, H., Dong, X., da Silva, E.B., de Oliveira, L.M., Chen, Y., & Ma, L.Q. (2017). Mechanisms of metal sorption by biochars: Biochar characteristics and modifications, *Chemosphere*, 178, 466–478. DOI: 10.1016/j.chemosphere.2017.03.072

Li, J., Chen, X., Yu, S., & Cui, M. (2023). Removal of pristine and aged microplastics from water by magnetic biochar: adsorption and magnetization, *Science of the Total Environment*, 875, 162647, https://doi.org/10.1016/j.scitotenv.2023.162647.

Liu, Z., Zhen, F., Zhang, Q., Qian, X., Li, W., Sun, Y., Zhang, L. & Qu, B. (2022). Nanoporous biochar with high specific surface area based on rice straw digestion residue for efficient adsorption of mercury ion from water, *Bioresource Technology*, 359, 127471, https://doi.org/10.1016/j.biortech.2022.127471.

Mahmud, A., Wasif, M.M., Roy, H., Mehnaz, F., Ahmed, T., Pervez, M.N., Naddeo, V., & Islam, M.S. (2022). Aquatic microplastic pollution control strategies: sustainable degradation techniques, resource recovery, and recommendations for Bangladesh, *Wate*r, 14, 3968. https://doi.org/10.3390/w14233968

Majewska, M., & Hanaka, A. (2025). Biochar in the bioremediation of metal-contaminated soils, *Agronomy*, 15(2), 273. https://doi.org/10.3390/agronomy15020273

Masinga, T., Moyo, M., Pakade, V.E. (2022). Removal of hexavalent chromium by polyethyleneimine impregnated activated carbon: intra-particle diffusion, kinetics and isotherms, *Journal of Materials Research and Technology*, 18, 1333, https://doi.org/10.1016/j.jmrt.2022.03.062.

Nazbakhsh, M., Nabavi, S.R., & Jafarian, S. (2025). Optimized production of high-performance activated biochar from sugarcane bagasse via systematic pyrolysis and chemical activation, *Sustainability*, 17(4), 1554. https://doi.org/10.3390/su17041554

Osman, A.I., Fawzy, S., Farghali, M., El-Azazy, M., Elgarahy, A. M., Fahim, R.A., Maksoud, M.I.A., Ajlan, A.A., Yousry, M., Saleem, Y., & Rooney, D.W. (2022). Biochar for agronomy, animal farming, anaerobic digestion, composting, water treatment, soil remediation, construction, energy storage, and carbon sequestration: a review, *Environmental Chemistry Letter*, 20, 2385–2485. https://doi.org/10.1007/s10311-022-01424-x

Patra, B.R., Mukherjee, A., Nanda, S. & Dalai A.K. (2021). Biochar production, activation and adsorptive applications: a review. *Environmental Chemistry Letter*, 19, 2237–2259. https://doi.org/10.1007/s10311-020-01165-9

Peng, G., Xiang, M., Wang, W., Su, Z., Liu, H., Mao, Y., Chen, Y. & Zhang, P. (2022). Engineering 3D graphene-like carbon-assembled layered double oxide for efficient microplastic removal in a wide pH range, *Journal of Hazardous Materials,* 433, 128672, https://doi.org/10.1016/j.jhazmat.2022.128672.

Prata, J.C., da Costa, J.P., Duarte, A.C., & Rocha-Santos, T. (2019). Methods for sampling and detection of microplastics in water and sediment: A critical review. *TrAC Trends in Analytical Chemistry,* 110, 150–159. DOI: https://doi.org/10.1016/j.trac.2018.10.029

Qu, J., Wang, Y., Tian, X. Jiang, Z., Deng, F., Tao, Y., Jiang, Q., Wang, L. & Zhang, Y. (2021). KOH-activated porous biochar with high specific surface area for adsorptive removal of chromium (VI) and naphthalene from water: affecting factors, mechanisms and reusability exploration, *Journal of Hazardous Materials*. 401, 123292, https://doi.org/10.1016/j.jhazmat.2020.123292.

Razeghi, N., Hamidian, A.H., Wu, C., Zhang, Y. & Yang, M. (2021). Scientific studies on microplastics pollution in Iran: An in-depth review of the published articles. *Marine Pollution Bulletin*. 162, 111901. https://doi.org/10.1016/j.marpolbul.2020.111901

Seow, Y.X., Tan, Y.H., Mubarak, N.M., Kansedo J., Khalid, M. Ibrahim, M.L. & Ghasemi, M. (2022). A review on biochar production from different biomass wastes by recent carbonization technologies and its sustainable applications, *Journal of Environmental Chemical Engineering*, 10, 107017, https://doi.org/10.1016/j.jece.2021.107017.

Shrivastava, A., Abhishek, K., Gupta, A.K., Jain, H., Kumari, M., Patel, M. & Sharma, P. (2024). Removal of micro- and nano-plastics from aqueous matrices using modified biochar – A review of synthesis, applications, interaction, and regeneration. *Journal of Hazardous Materials,* 16, 100518. https://doi.org/10.1016/j.hazadv.2024.100518

Siipola, V., Pflugmacher, S., Romar, H., Wendling, L., & Koukkari, P. (2020). Low-cost biochar adsorbents for water purification including microplastics removal, *Applied Sciences,* 10, 788. DOI: 10.3390/app10030788

Singh, N., Khandelwal, N., Ganie, Z.A., Tiwari, E., & Darbha, G.K. (2021). Eco-friendly magnetic biochar: An effective trap for nanoplastics of varying surface functionality and size in the aqueous environment, *Chemical Engineering Journal,* 418, 129405, https://doi.org/10.1016/j.cej.2021.129405.

Sun, Y., Shaheen, S.M., Ali, E.F., Abdelrahman, H., Sarkar, B., Song, H., Rinklebe, J., Ren, X., Zhang, Z., & Wang, Q. (2022). Enhancing microplastics biodegradation during composting using livestock manure biochar. *Environmental Pollution,* 306, 119339. DOI: 10.1016/j.envpol.2022.119339

Titone, V., Botta, L., & La Mantia, F.P. (2024). Mechanical recycling of new and challenging polymer systems: a brief overview, *Macromolecular Materials and Engineering*, 2400275. https://doi.org/10.1002/mame.202400275

Tiwari, E., Singh, N., Khandelwal, N., Monikh, F.A., & Darbha, G.K. (2020). Application of Zn/Al layered double hydroxides for the removal of nano-scale plastic debris from aqueous systems. *Journal of Hazardous Materials*. 397, 122769. https://doi.org/10.1016/j. jhazmat.2020.122769.

Tong, M., He, L., Rong, H., Li, M. & Kim, H. (2020a). Transport behaviors of plastic particles in saturated quartz sand without and with biochar/Fe_3O_4-biochar amendment, *Water Research*, 169, 115284, https://doi.org/10.1016/j.watres.2019.115284.

Tong, M., Li, T., Li, M., He, L., & Ma, Z. (2020b). Cotransport and deposition of biochar with different sized-plastic particles in saturated porous media. *Science of the Total Environment,* 713, 136387. DOI: 10.1016/j.scitotenv.2019.136387

Wang, J., Sun, C., Huang, Q.X., Chi, Y., & Yan, J.H. (2021a). Adsorption and thermal degradation of microplastics from aqueous solutions by Mg/Zn modified magnetic biochars. *Journal of Hazardous Materials,* 419, 126486. DOI: 10.1016/j.jhazmat.2021.126486

Wang, T., Zhang, D., Fang, K., Zhu, W., Peng, Q., & Xie, Z. (2021b). Enhanced nitrate removal by physical activation and Mg/Al layered double hydroxide modified biochar derived from wood waste: Adsorption characteristics and mechanisms. *Journal of Environmental Chemical Engineering*, 9, 105184. DOI: 10.1016/j.jece.2021.105184

Wang, R.P., Zhang, S.Y., Chen, H.L., He, Z.X., Cao, G.L., Wang, K., Li, F.H., Ren, N.Q., Xing, D.F., & Ho, S.-H. (2023). Enhancing biochar-based nonradical persulfate activation using data-driven techniques, *Environmental Science & Technology*, 57 (9), 4050–4059. https://doi.org/10.1021/acs.est.2c07073

Wu, J., Yang, C., Zhao, H., Shi, J., Liu, Z., Li, C., & Song, F. (2023). Efficient removal of microplastics from aqueous solution by a novel magnetic biochar: performance, mechanism, and reusability, *Environmental Science Pollution Research*, 30, 26914, https://doi.org/10.1007/s11356-022-24130-1

Yao, S., Ni, N., Li, X.A., Wang, N., Bian, Y.R., Jiang, X., Song, Y., Bolan, N.S., Zhang, Q.Z., & Tsang, D.C.W. (2023). Interactions between white and black carbon in water: a case study of concurrent aging of microplastics and biochar, *Water Research,* 238, https://doi. org/10.101 6/j.watres.2023.120006.

Zhang, L., Zhang, Q., Wang, Y., Cui, X., Liu, Y., Ruan, R., Wu, X., Cao, L., Zhao, L. & Zheng, H. (2023). Preparation and application of metal-modified biochar in the purification of micro-polystyrene polluted aqueous environment, *Journal of Environmental Management*, 347, 119158. https://doi.org/10.1016/j.jenvman.2023.119158

Zhu, N., Yan, Q., He, Wang, X.Y., Wei, Z.A., Liang, D., Yue, H.F., Yun, Y., Li, G.K., & Sang, N. (2022). Insights into the removal of polystyrene nanoplastics using the contaminated corncob-derived mesoporous biochar from mining area, *Journal of Hazardous Materials*, 433, 128756. https://doi.org/10.1016/j.jhazmat.2022.128756.

Review Article

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Impact of livelihood-based social protection on climate change adaptation: evidence from Rural Ethiopia

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Abstract

The concern of climate change and its multifaceted social, economic, ecological, cultural, and political effects spire almost all developing countries. This requires a long-term commitment from government and non-government developmental entities. As well broadened understanding of how human societies – and the activities that take place within them – drive climate change. So, this review paper aims to analyze and examine climate change-induced effects, and the impact of livelihood-based social protection on climate change adaptation of rural communities in Ethiopia. This has been carried out via a systematic literature review method to map out the thematic field under investigation through a scoping review and comprehensive assessment of findings, research, and practices regarding the concern of climate change. Indeed, most of the climate action undertaken in the rural part of the country lacks inclusiveness. Which is much more emphasized and viewed through the lens of ecological aspects. This undermines and neglects deep-rooted rural communities' livelihood systems and the social and attitudinal dimensions. Therefore, a rights-based approach holds considerable promise for injecting urgency and ambition into global climate action. While safeguarding the most vulnerable people in rural society focusing on equity and social justice offers both a compelling moral and ethical argument for action rather than the authoritative basis of advocacy. It helps to give voice to the most vulnerable groups, through designing livelihood-based social protection schemes as an approach and strategy for future climate change adaptation and mitigation action in the rural parts of the country.

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Introduction

Climate change is widely acknowledged as foremost among the formidable challenges facing the international community in the 21st century. It poses challenges to fundamental elements of our understanding towards appropriate goals for social, and economic policy, through connecting economic growth, equity, and sustainable development. For most developing countries climate change is known as one of the most urgent and complex challenges for rural societies and their economies (UNDP, 2007). Which complicates existing challenges of poverty eradication (Adger et al., 2003) and the realization of Millennium Development Goals. Left unaddressed climate change contains the potential to reverse progress on sustainable development and compromise the well-being of the current and future rural communities' generations. Adaptation to climate change is necessary for all countries that seek to reduce the current impacts of climate change and increase resilience to future impacts. It is highly relevant for developing countries whose societies are already struggling to meet the challenges posed by existing climate variability (Yamin et al., 2005; Adger et al., 2003). For these countries, adaptation has grown from a minor environmental concern to a major challenge for human development and a crucial element in eradicating rural poverty (Davies et al., 2008), and food insecurity. The term adaptation is described and defined in various types and forms, including anticipatory and reactive adaptation, and autonomous and planned adaptation. To distinguish this, IPCC[1] (2007) referred to adaptation as the adjustment in natural or human systems in response to actual or expected climatic stimuli and their effect to moderate harms and exploit beneficial opportunities.

According to IPCC (2007) a case for more extensive adaptation by the need for a deep understanding of options and barriers to adaptation which is not fully understood. Moreover, the dominant discourse of adaptation is a top-down managerial approach starting with international bodies cascaded to national authorities through negotiations and financial transfers. Rural communities have important long-standing adaptation skills and experiences for tackling hazardous environmental conditions including climate variability (Ware, 2022). Whereby national and international climate policy regimes fail to reach the poor and vulnerable rural communities or they tend to plan interventions for communities instead of supporting initiatives led by rural communities (Yamin et al., 2005). To be effective, global efforts need to be aligned with local realities and focused 'on how policy can support the adaptive capacity and resilience of vulnerable rural communities' (Adger, 2003). Among the various adaptation strategies used by rural communities, including crop diversification, soil, and water conservation, and small-scale irrigation (Ware, 2022), which have a direct impact on their livelihood system.

According to Maddison (2007) expression given the impacts of climate change on livelihoods, response efforts to address contain two vital steps. The first is to perceive the risks of climate change, the second is to decide on adaptation measures. Both steps involve risk management and decision-making. Most rural People's perceptions are contextual, and grounded on complex sets of social, political, and

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environmental settings. Perceptions about climate change and especially about its causes are filtered through local knowledge, values, and moral norms. The IPCC (2007) recognized that the perception of climate change is about human behavior, which is one of the least understood components of the climate system. Therefore, it is important to understand how differently situated rural communities perceive, interpret, and act on climate change. The importance is magnified in the face of the claim that climate vulnerability studies ignore local perceptions and contexts that define quality of life and well-being (O'Brien et al., 2004).

Ethiopia is experiencing the negative effect of climate change and unpredictability on several front, including crop productivity, livestock production and rearing, land productivity, water availability, biotic growth, and rang-land quality and soil productivity (Daba et al., 2025). This shows that the country main sources of livelihood - agricultural sectors food production, and among of income generated from it negatively impacted by climate change on a national level. The country's concerns over the impact of climate change and variability on agriculture and food security have grown which have been highlighted in most recent years (Sinore & Wang, 2024). Due to the effects of climate change and its unpredictability there is highly growing need to further develop and execute adaptation and mitigation measures (Sinore & Wang, 2024). country's vulnerability to climate change variability is particularly pronounced because of dependency on rain-fed agriculture and natural resources as a driver of economic growth (Dendir et al., 2019; Sinore & Wang, 2024).

Despite in-built resilience factors, there is no denying that rural communities in Ethiopia are most affected since their livelihoods are directly dependent on climate-sensitive economic sectors, namely, agriculture. In this case, 95% of agricultural activity is dependent on rainfall to the extent that the country's GDP growth rate is closely associated with the pattern of rainfall distribution and agricultural production. However, such a link is weaker than originally thought (Conway & Schipper, 2011). Nonetheless, the link persists in less diversified agricultural systems dominated by few crops. Agricultural production in these systems is generally affected by climatic variables such as temperature, precipitation, wind conditions, and water availability. According to the IPCC (IPCC, 2007), rising temperatures and changing precipitation patterns affect crop growth, livestock performance, water availability and the functioning of ecosystem services. In the meanwhile, the World Bank (2008) recognizes that due to rising temperatures, rural people's exposure to malaria, dengue, and cardiovascular illnesses increases especially in the tropics. It expects diseases to increase up to five percentage in countries with per capital incomes below $6,000, while declining agricultural yields in some regions would increase malnutrition, thus reducing people's resistance to illness. The World Health Organization also predicted that the above diseases would worsen as the result of climate changes in which the lives and livelihood systems of the most vulnerable social groups become much more unprotected.

Like many other developing countries Ethiopia face the challenges posed by climate change and has been taken several measures to adapt to and mitigate its impact (Sinore and Wang, 2024). Despite, devoting significant efforts to implementing adaptation and mitigation strategies and approaches to tackle the challenges of climate change the country encounters significant limitation with these strategies and approaches. Therefore, to deal with the issues and to comprehend and overcome these limitations is imperative for the success and enduring the effectiveness of climate change initiatives at national, regional, and local level. According to Sinore & Wang (2024) a range of ecological and sociocultural factors influence the country's sustainable uses of climate change strategies. These factors are interconnected and can significantly impact the success or failure of adaptation efforts undertaken either by government or non-governmental development entities. For instance, the country mostly characterized by diverse ecological zones, including highland, lowland, and arid regions with diverse topography creating a varied climate landscapes, such as changing rain fall patterns, increasing temperature, and land degradation. This poses substantial challenges to adaptation and mitigation efforts, in the highland parts of the country crop production is the primary means of livelihood system, shifting in precipitation and temperature impact crop yields. Whereas, in the pastoral and agro-pastoral communities in the arid and semi-arid lowland regions face challenges, including dwindling of water resources, loss of livestock grazing land, and disease outbreak. Therefore, these ecological factors shape the specific needs and priorities of these communities resides at different ecological zones of varied regions of the country. In the meanwhile, sociocultural factors are essentially crucial in influencing climate change adaptation strategies given the nation's diverse culture leading to a distinct sociocultural dynamic. Rural communities' traditional practices and knowledge system, as well as sociocultural norms play significant role in determining how rural communities respond to climate change, and often relay on indigenous practices and local knowledge at a foundation of adaptation strategies (Sinore & Wang, 2024).

Despite that, there is a growing recognition of the role of social protection in addressing various livelihood shocks and vulnerabilities to the effect of climate change. Many social protection schemes have targeted and contributed to the efforts to reduce vulnerabilities and create more inclusive and sustainable development pathways (Mesquita & Bursztyn, 2016). Thus, in recent decades, several developing countries that developed and strengthened their social protection systems following the success of Latin American countries (Cirillo & Tebaldi, 2016). Therefore, this review paper aims to critically discuss, and examine the knowledge gaps and limitations of social protection policy framework towards climate change adaptation and mitigation action in the context of rural communities. So, to analyze climate change-induced effect on the livelihood of rural Ethiopia, systematic review methods were employed accompanied by narrative analysis. Through a detailed review of existing literature (articles, books, research and reports), including debates relevant to this particular topic area of emphasis. Specifically, it gives due emphasis on the social dimensions of climate change and livelihood-based social protection. As well as analyze and discuss climate change adaptation national plans, policies, strategies, development programs and projects with the idea of a sustainable and equitable rural development perspective. Which is understood as "an irreducible holistic" framework where economic, social and environmental issues interdependent, while focusing on vulnerable rural communities and social groups that must be approached within a unified framework.

Materials and Methods

Systematic literature review

The goals of the literature review depend on which type of literature review to answer specified as well as concentrated research questions. That is why the method of systematic literature review can reduce bias in literature analysis (Booth et al., 2016). For this article systematic literature review is employed to identify, evaluate as well and summarize relevant studies to show a synthesis of evident climate change adaptation and mitigation action. To critically discuss and analyze climate change-induced effects on the livelihood of rural Ethiopia detailed review of existing literature, and debates relevant to this particular topic area of emphasis have been given. Through enumerating, describing, summarizing, and objectively evaluating the existing literature on climate change adaptation and mitigation action to determine what is known about climate-induced effects, national adaptation plans, and social protection policies. This enables how well-established knowledge will direct future research that might best be undertaken.

Jesson et al. (2011) suggested that systematic reviews have a clearly stated purpose, questions, a defined research approach and an appraisal of the articles. By following an explicit research methodology, the weaknesses of traditional approaches shall be overcome (Harden & Thomas, 2010). These weaknesses may include biases and philosophical mix-ups through heterogeneous sampling (Petticrew, 2001), or issues with the quality of assessment. Following this, the following steps have been undertaken.

Phase 1- Mapping the field through a scoping review: Conducted a systematic literature review of the scope of the amount of relevant material, by identifying the most often cited texts and following up on the references therein. This gave the first impression of existing knowledge and knowledge gaps under this topic.

Phase 2- Comprehensive search: Here entered into the systematic literature review by using the process described through searches in keywords, titles, abstracts, and some themes using Google Scholar with other combinations of the search terms; Aligned with climate change-induced effect. This enables to presentation comprehensive background of the literature within the topic to highlight new research streams by identifying gaps or recognizing inconsistencies for refining, focusing, and shaping the direction for further research.

Phase 3- Quality assessment: The search was subsequently limited to specific publications related to ethnicity and minority in the urban context.

Phase 4- Data extraction. The articles were analyzed along with the nature of the article (empirical or conceptual), analysis method, theoretical perspective, findings or results, definitions or propositions, and quality-related comments have been summarized. To identify the main categories of this literature, the strategy was first to obtain a broad understanding of these articles, list the keywords of all of the selected articles, and summarize additional keywords by reviewing abstracts, introductions and findings. By grouping the keywords able to identify first-order concepts. Then continued by grouping these keywords into categories.

Phase 5- Synthesis: Relevant identified concepts and supporting sources identified to construct major themes, then analyzed pertinent to the finding of each reviewed article.

Phase 6- Write-up and diffusion: The next section addresses the synthesis of the analysis of the articles as a result and discussion of this article.

Result and Discussion

Dimensions of climate change

The concept of climate change has a wide range of meanings and definitions, and it is defined in various ways by social and natural science researchers across different disciplines and development practitioners. Indeed, almost agree that climate change is the global phenomenon of climate transformation characterized by the change in the usual climate of the planet (regarding temperature, precipitation, and wind, etc) that are especially caused by human activities. As a result of the weather of the earth, the un-sustainability of the planet's ecosystem become under threat as well as the future of human kinds, and the stability of the global economy, and social well-being. According to the United Nations Framework Convention on Climate Change (UNFCCC, 2021), "Climate Change" is defined as a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable periods. While the concern of climate change has a broad range of phenomena created predominantly by burning fossil fuels which add heat-trapping greenhouse gasses to the earth's atmosphere, these phenomena include the increased temperature trends described by global warming but also encompass changes such as sea-level rises (NASA, 2021). To be effective, global efforts need to be aligned with local rural communities' realities and focused 'on how policy can support the adaptive capacity and resilience of vulnerable communities (Adger et al., 2003). To deliver climate action UNDP (UNDP, 2024), embraces a partnership approach between local, national and regional levels, including the private sectors across the globe.

Ecological/Environmental dimension

The ecological dimension of climate change deals with the fragility of ecological and biophysical systems and their different functions under hazardous conditions to suffer damage and deterioration Kienberger & Zell (2014) in rural human society. Which describes the interaction that occurs between humans and natural aspects of the environment as well as the effect that they have on one another. Despite this, ecosystems are exposed to the effects of changing climates in different measures. However, the impacts of climate change may be difficult to detect since they are often combined with the effects of other activities, such as rural communities land use changes undertaken human ecology. The Global Biodiversity Outlook report (UNEP, 2010) identifies climate change as one of the main factors responsible for the current loss of biodiversity. Some aspects of biodiversity loss in the rural part of the country, including deforestation and the draining of wetlands, will exacerbate climate change by releasing centuries' worth of stored carbon to the environment. In the meanwhile, according to the UN Secretariat of the Convention on Biological Diversity (2010), climate change affects different ecosystems in different ways. Depending on the complexity and original characteristics of the system, geographical location and the presence of factors that may regulate the extent of the changes in the ecosystem. Degraded ecosystems are generally believed to be less resilient to climate change than intact ecosystems. Indeed, the increase in mean annual temperature is already affecting many ecosystems. Scientific studies predict that future changes will be much greater amplitude which will lead to the loss of the natural resource-based livelihood system of most rural communities in Ethiopia.

Economic and livelihood dimension

Livelihoods are the means that enable rural people to earn a living, this includes the capabilities, assets, income, and activities rural communities require to ensure that their basic needs are covered (Chambers & Conway, 1991). Therefore, a livelihood is sustainable when it allows rural people to cope with, and recover from setbacks and stress (such as natural disasters and economic or social upheavals), and improve the welfare of future generations without degrading the environment or natural resources base (Chambers & Conway, 1991). Dejen et al. (2024) argue that in rural communities to cope and survive the effect of disaster risk, livelihood diversification has a relevant impact, as well as for poverty reduction and to improve food security. However, changes in the mean climatic conditions (such as temperature and precipitation) affect soil moisture, water availability, and the incidence and distribution of plant and animal pests and pathogens. Eventually, these impinge on the growth and development of crops (Hertel & Lobell, 2014). Due to this given set of inputs, climate change is often regarded as analogous to technical change affecting agricultural production and rural communities' livelihood. Not only, has climate change also made future rural livelihood prospects unpredictable and unreliable which in turn may trigger out-migration either to increase earnings or to spread out risks. The impacts of climate change on agriculture are expected to be immediate, negative, and stronger in sub-Saharan African countries. This stems from the existing environmental conditions, least diversified and poor rural economies, and low level of agricultural development despite it being the main contributor to exports and the GDP of the country.

Human and social dimension

The social dimensions of climate change are those that relate to, in particular; health, gender, population dynamics, human rights, migration, access to decent work, and social protection for those most vulnerable social groups of rural society (UN, 2011). Unequivocal scientific evidence marshaled by the United Nations' Intergovernmental Panel on Climate Change (IPCC, 2007) shows that greenhouse gas (GHG) emissions from human activity—particularly burning fossil fuels for energy—are changing the Earth's climate. In the social dimension of this complex phenomenon, a detailed understanding is needed to underpin an effective global response. As a recent Human Development Report made clear, there are glaring inequities in the distribution of responsibility for the causes of global warming and the distribution of its impacts among the nations and peoples of the world (UNDP, 2007). Poor rural people in developing countries bear the brunt from its impacts while contributing very little to its causes. However, the human and social dimensions of climate change have been woefully neglected in the global debate—at least, until recently.

Without vigorous adaptation and mitigating measures, climate change is projected to further exacerbate the vulnerabilities of most marginalized rural people, place human health and security at risk, and impede sustainable development. Integration of social dimensions into these measures is vital (UN-HLCP, 2011). People are not only the victims of the negative impacts of climate change, they are the drivers of climate change, as well as the essential agents for redirecting development trajectories. This understanding–of the central role of people, social dimensions, and institutions–can profoundly reshape how policy-makers craft and implement climate change policies and strategies. This is mainly important juncture when nations are committing to more robust climate change mitigation and adaptation strategies. The international community is deliberating on core elements of the next climate change paradigm amid pressing expectations for concrete results. At its most basic level, climate change impacts people and response measures, which depend on people themselves to be successful. The social dimensions of climate change and the interplay that exists between climate as a phenomenon, related policy and society, including the role of people as the victims, and agents of climate change are the most critical to the success of climate policy. To date, however, in most developing countries the human variable of the climate equation has been too frequently missing. As a result, the impact of climate change will increasingly affect the daily lives of rural people everywhere across the world in terms of employment and livelihood, health, food security, access to clean water and housing, as well as the realization of gender equality and human rights. These impacts are expected to hit harder those living in poverty due to their more prevalent dependency on the very natural resources affected by climate change. This is because they have less capacity to protect themselves, adapt and recuperate losses. Effective policies and measures to address these impacts and to reduce greenhouse gas emissions in large part depend on these same people, and thus largely depend on the transformation of social and economic relations that contribute to their vulnerability (UN-HLCP, 2011).

According to multiple sources of literature case studies and lessons learned from the history of human development, the inclusion of social dimensions is essential when the most powerful and resource-intensive Western societies are to change their consumption habits and patterns. Therefore, there is a need to establish essential synergies between the climate change agenda and complementary sustainable development and human rights agendas, both in terms of their objectives and their means of achievement. Through integrating social dimensions in climate policy, these synergies have significant potential to amplify concrete results to climate change adaptation and mitigation action via livelihood-based social protection schemes in most rural communities of the nation.

Policy and institutional framework

The policy framework for climate change mitigation and adaptation has progressively evolved since the ratification of the United Nations Framework Convention on Climate Change (UNFCCC) in 1994. As part of its commitment, Ethiopia submitted to the UNFCCC its Initial National Communication (INC) in 2001 and Second National Communication (SNC) in 2015. The country also launched the National Adaptation Plan of Action in 2007, the Ethiopian Program of Adaptation on Climate Change, and Nationally Appropriate Mitigation Actions in 2010. The country has endorsed a Climate Resilient Green Economy (CRGE) strategy to build a green and resilient economy in 2011. Apart from this, sectoral policies and strategies have been formulated to provide tailored and sector-specific strategic interventions. These include: the Climate Resilience Strategy for Agriculture and Forestry (2015); the Climate Resilience Strategy for Energy and Water (2015); the Climate Resilient Strategy for the Transport Sector (2015); the National Health Adaptation Plan to Climate Change (H-NAP, 2017) and the Climate Resilience Strategy for

Urban Development and Housing (2017). In addition, for climate change adaptation contribution (NDC), Ethiopia has been putting in place various policy actions that enhance the implementation of climate change adaptation over the last decade. Core policy and institutional measures have been materialized by mainstreaming climate change adaptation into national and sectoral plans with an emphasis on implementing identified adaptation options across selected sectors.

Given the vulnerability of the country and less adaptive capacity to absorb external shocks emanating from the devastating effects of climate change including hazards such as drought and floods, the government of Ethiopia has made Adaptation a priority. Within this context, prioritization of adaptation interventions becomes a powerful approach to ensure the effective and efficient utilization of the scarce resources available.

Whilst, the initial national climate change strategy- the CRGE Strategy- did not sufficiently contain adaptation and resilience. Even though several sectors have affirmed the importance of building adaptive capacity to reduce rural communities' vulnerability as adaptation interventions grew substantially. Most recently, NAP formulated in 2017, spanning the agriculture, forestry, health, transport, energy, industry, water, and urban sectors reaffirmed this importance. Furthermore, the NAP implementation roadmap expanded the options. Despite this, is outlined under the NAP with actions, categorized into short-term priorities, such as capacity building, strengthening the enabling environment, and promoting research, with long-term priorities of sector-specific activities. In addition to the long-term priorities, from the NAP implementation roadmap, several potential adaptation commitments have been considered for inclusion in the NDC. The selection of 18 climate change adaptation options under the NAP, and the numerous adaptation actions under the implementation roadmap already reflect a lengthy, rigorous officially endorsed prioritization process that entailed in-depth stakeholder participation as detailed in the NAP's methodology of the country. This has been informed by an extremely broad range of national, sectoral, and technical studies (as noted in the NAP implementation roadmap methodology). Where an attempt was made to further prioritize a sub-set of interventions in the updated NDC of the country. Prioritization criteria were developed to select the optimal interventions (from within the NAP's adaptation options and the NAP Implementation Road-map's supplementary adaptation actions). The national NAP's and NDC internationally recognized and widely used PEStLE framework - as an analytical framework for multi-criteria decision making have been applied to each of the PEStLE categories, including economic, social, technological, legal (institutional), and environmental with four relevant criteria. Using the prioritization criteria to evaluate each adaptation option from the NAP, and each long-term adaptation action from the NAP implementation roadmap is so essential. Nearly 20 steps have been taken for each of the 52 interventions screened, ranging from cross-referencing with the ten Yearly Development Plan (YDP). Which include NAP-ETH relevant sectoral climate resilience or adaptation strategies aligned with the Sendai framework for disaster risk reduction, and African Union's Agenda 2063, and the AU's draft strategy on climate change 2015.

National adaptation plan

The national adaptation plan of the country (NAP-ETH) has been developed on ongoing efforts to address climate change in the country's development policy framework, including the climate resilient green economy strategy, and the second growth and transformation plan (GTP-II), as well as sectoral climate resilience strategies, and regional, and municipal adaptation plans. Its goal is to reduce rural communities' vulnerability to the effects of climate change through building adaptive capacity and resilience. The country NAP-ETH aims to strengthen the holistic integration of climate adaptation action in the country. Indeed, the long-term development pathway is supported by effective institutions and governance structures, finance for implementation and capacity development, and a strengthened system for disaster risk management, and integration among different sectors (NAP-ETP, 2019; FDRE, 2021) which is detail described under the national adaptation plan of the country.

Despite, viewing climate change as a problem that is social in both its causes and consequences, it requires a detailed explanation to contribute to the study of climate change. In recent decades, analyzing attitudes to climate change, the adoption of green behaviors, and issues of climate justice, has become clear from two recent reviews (Dietz et al. 2020; Klinenberg et al., 2020). Climate change rarely features outside field-specific journals, and there remain significant gaps in understanding the social nature of climate change as a global concern. As a global collective action problem; Hardin's (Hardin,1968) on 'the tragedy of the commons' neatly demonstrates that individual actors often lack the motive to take public interests, such as the preservation of the environment, fully into account. When their goal is to maximize utility in the short run, it can be entirely rational for actors to exploit collective resources, even when the whole community will eventually suffer losses as a result. This represents a classic case of a collective action problem or social dilemma, with every actor facing motives not to take any precautionary actions. Even though a collective failure to act will ultimately harm everyone's welfare and social protection, more significantly the rural communities.

Social protection typology

Social protection interventions are key supporters of inclusive rural transformation but require alignment with broader inclusive policies (Trivelli et al., 2017). Contextualizing social protection as a part of and fully integrating with anti-poverty policies, with such policies themselves being broadly convinced given the complex, multi-dimensional nature of poverty and deprivation Guhan (Guhan, 1994) distinguishes three types of social protection-related measures: protective, with the specified objective of guaranteeing relief from deprivation; preventive, directly seeking to avert deprivation in various ways; and promotional, aiming to enhance real incomes and capabilities (Trivelli et al., 2017). Despite this, this classification makes a methodological contribution in terms of highlighting the progressiveness from general to specify social protection measures towards rural communities' livelihood transformation.

Social protection policy trend

The government of Ethiopia recognizes the contribution of social protection to the realization of the development goals of the country and commits substantial human and financial resources to maximize the reach and impact of such programs to its poorest and most vulnerable rural communities (World Bank, 2024). Social protection is not a new instrument in many African countries, and a wide range of social protection schemes after interdependence, including the provision of free health care, pensions for government employees, and food and agricultural subsidies. However, following the implementation of structural adjustment programs (SAPs, domestic expenditure on these items was reduced, and many programs were scaled down or terminated (UNEC, 2009). Hence during the 1990s, social protection programming was largely implemented in response to the negative impacts of structural adjustment policies, particularly in Latin America but also in Africa and Asia (Slater & McCord, 2009). This approach drew on the social risk and management framework developed by the World Bank in the 1990s (Holzmann & Jorgenson, 1999), and as a result, World Bank thinking dominated the design and implementation of social protection provision in middle and low-income countries. This approach promoted a residual form of social protection based on supporting those adversely affected by structural adjustment, and primarily concerned with the provision of social safety nets, as a response to shocks (Slater and McCord, 2009).

Under this approach, the role of government in the provision of social protection was limited to the implementation of social safety nets for risk coping (Devereus and Wheeler, 2004). Although by the turn of the century, the World Bank's position had widened somewhat from the safety net approach to take on a wider concept of social protection Holzmann and Jogensen (Holzmann & Jorgensen, 2000), the Bank's approach is still widely criticized for the fundamental underlying assumption that risk management the poor will be bounced out of poverty (Meth, 2008). While structural adjustment stimulated a range of interventions to support the poor through the temporary negative impacts of the adjustment process, one type of program in particular - conditional cash transfers - received strong support from the World Bank and Inter-American Development Bank in this way came to dominate social protection practices in Latin America (Slater and McCord, 2009). This domination continues to the most recent years. In Africa, the establishment of social action. Investment funds were a more common response, and these funds were frequently associated with the adoption of public works programs, providing short-term employment opportunities, as the dominant approach for delivering welfare to poor households, rather than a cash transfer approach (Slater and McCord, 2009). Social funds, largely funded by the World Bank, remain a cornerstone of social protection response across the African continent (Slater and McCord, 2009).

Social protection schemes change in Ethiopia

In Ethiopia, emergency appeals for humanitarian support have been launched every year since the famine of 1984, and in many parts of the countries, essentially predictable and chronic hunger has come to be characterized as unpredictable emergencies requiring repeated humanitarian response (Slater and McCord, 2009). Such a crisis led to a shift in the design of the response by the government and the international community, based on the realization that rather than the repeated humanitarian response at the time of acute need, a more appropriate response would be designed to address chronic vulnerability and the structural factors underlying vulnerability by implementing social protection programs, in coordination with a range of other development initiatives (Slater and McCord, 2009). The consequence was a radical change in programming attempting to develop a predictable and medium-term response to the crisis. The result has been the emergency of medium-term developmental response which aims to meet not only immediate needs but also contribute to the reduction of vulnerability by promoting livelihoods, which also addresses the factors that cause vulnerability through the provision of appropriate infrastructure and systems. The Productive Safety Nets Programme (PSNP) in Ethiopia is the largest of such programs and has been designed to include medium-term intervention that contributes to protective, promoted and transformative social protection, focusing on support for developmental activities which are productivity-enhancing and environmentally protecting, as well as providing resources at household level (Slater and McCord, 2009).

The link between social protection and rural livelihood

According to Dorward et al., (2006), the link between social protection and agricultural growth in rural communities goes beyond positive feedback where reduced vulnerability promotes growth and reduced vulnerability. Social transfer has an effect if it takes rural people or economies across critical poverty trap thresholds and impacts also depend on other social protection schemes intervention in rural communities. Even though complementary roles for social protection and rural agricultural development policies revolve around their contribution to poor peoples' hanging in, stepping up, and stepping out strategies. The newer insurance and resilience-based social protection instruments may help people to escape from poverty traps so that they can step up or step out taking risks to engage in more productive activities (Dorward et al., 2006). As yet, the link between social protection schemes and rural livelihood is not strongly interlinked with climate change mitigation and adaptation action in the rural communities of Ethiopia.

Vulnerability of rural community to climate change induced disaster

For several decades the country has been vulnerable to the effect of climate change induced multiple disastrous events that affected the economic, social and environmental well-beings of most rural communities. In which overall lives and livelihood system mainly relays on over-sensitive sector i.e agriculture which makes it more vulnerable to the effects of diverse natural and man-made disasters. According to World Bank (2025) report nearly 22.4million peoples were affected by disastrous events, including drought and food insecurity (20 million), flooding (1.5 million), conflict (794,000), earthquake (90,000), and landslide (29,000) peoples have been severely affected within the last three years. Under Figure 1 described below the occurrence of drought and flood insecurity in most rural parts of the country more severe than other types of disastrous event. Whereas, flooding, and conflict takes the second and third paces compared to earthquake. To overcome these climate induced effects government adapted varied mitigation and adaptation strategies through social protection schemes to build and strengthen the resilience and cope - up capacity. Even though the strategies and approaches were inadequate due to limited consideration of local communities' socio-cultural and environmental factors.

Table 1. Rural communities vulnerability context to climate change induced disasters between 2023 - 2025 (Source: World Bank, 2025)

Disastrous events	Years	Number of People affected	Percentage
Drought and Food Insecurity	2023 - 2025	20,000,000	89.2%
Flooding	2023 - 2025	1,500,000	6.7%
Conflict	2023 - 2025	794,000	3.5%
Earthquake	2023 - 2025	90,000	0.4%
Earthquake	2023 - 2025	29,000	0.12%

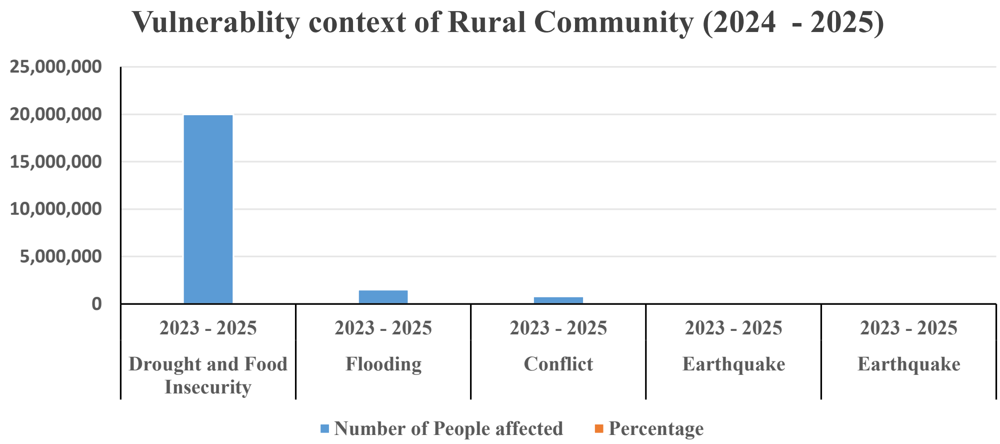

Fig1. Vulnerability context of rural community between 2024 - 2025 (Source: world bank 2025)

Climate change-induced livelihood impact

Impact on agricultural sectors

The effect of climate change on rural livelihood is so much more multifaceted. According to MoFED (MoFED, 2021), agriculture remains the main activity in the Ethiopian rural economy, contributes on average 44% of GDP, and employs over 80% of the population. Smallholder rural households in the country produce more than 90% of the agricultural outputs and cultivate more than 90% of the total cropped land. As a result, crop production is the dominant sub-sector accounting for more than 60 percent of agricultural GDP, followed by livestock with 20 percent (EDRI, 2021). It is estimated that 16.5 million hectares (14.8%) of the country's land area is potentially suitable for agricultural production. The potential irrigable land in the country is about 3.7 million hectares (MoFED, 2021). The country has the largest livestock population in Africa, and tenth–largest in the world with about 70 million head of livestock (EDRI, 2021). With a current growth rate of about 2.8 percent per year, Ethiopia's population is expected to reach 129 million by 2030 (Rahel et al., 2021). Almost two million persons are added annually to the population. Given the high proportion of the population living in rural areas, this will increase pressure on natural resources accompanied by increasing demand for productivity and scarce arable land at the expense of greener land uses such as pasture, and forests which will bring further degradation to the ecological well-being.

Its impacts in 2030 on GDP are progressively worse as the climate change-induced shocks become harsher (World Bank, 2008). In the worst-case scenario, real GDP in the final year would be 46 percent lower than in the base run. While productivity shocks occur only in the agricultural sectors, the negative impact also spreads across the economy. A simulation result of the CGE model showed that a 5.5 % reduction in the agricultural output has created a 10 % increase in the price level (Wolde, 2008). The same study revealed that from the industrial sector, the public agro-industry suffers the most damage with a 17 % reduction in output from climate change (EDRI, 2021). Under Figure 2 illustrated that impact of climate change on the agricultural sectors more severe on crop sub-sub sectors (60%), as compare to livestock sub-sector (20%).

Impact on non-agricultural sectors

Since the agricultural sector has a larger contribution to the country's economy, it is strongly linked with the non-agricultural sectors. The impact on this sector adversely affects the industry and service sectors of the economy (EDRI, 2021). Where the national productivity of the agricultural sector falls, in the meanwhile the industry and services sectors will decline consecutively. This simulation result scenario of the reduction in the total agricultural production leads to higher losses in the industrial sectors, and also the value of grain mill products, and prepared foods will decline by 27.6 and 24.9 percent in 2050 (Rahel et al., 2021; EDRI, 2021). Indeed, the service sector is also projected to decline by 24.6 percent and 33.9 percent, while hotel service decrease by 18.2 and 24.3 percent by 2040 and 2050, respectively (Rahel et al., 2021; EDRI, 2021)). Even though this projection focuses on certain sectors, climate change is so much more complex and its effect is further manifested in the rural social, and cultural system of rural communities. As described under Figure 3 the impact of climate change on non-agricultural sector by 2050 expected more significant on service sector (33.90) compare to industrial sector (24.90%), and others (24.30%).

Impact on household income

The rising prices of staple commodities may result in a substantial reduction in real income and an increase in poverty of households since their food consumption takes the highest share of the

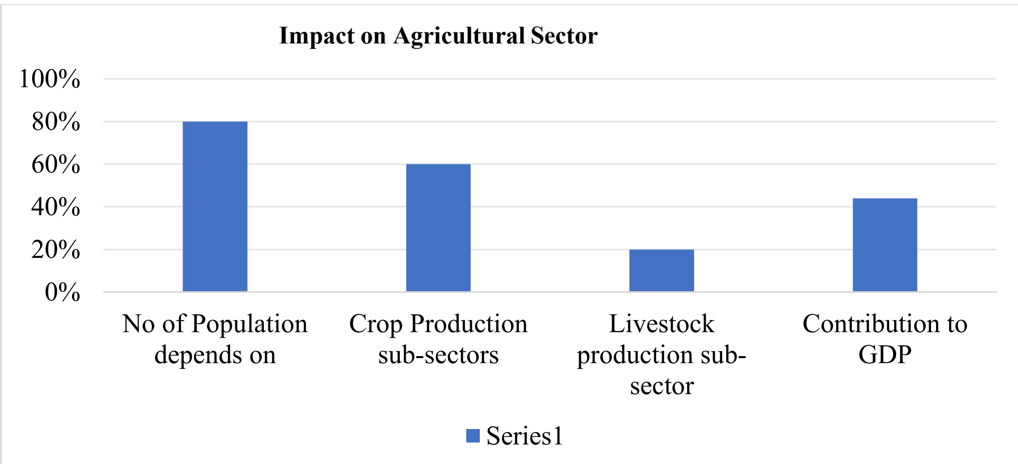

Fig 2. Impact on Agricultural sector (Source: Rahel et al., 2021; EDRI, 2021)

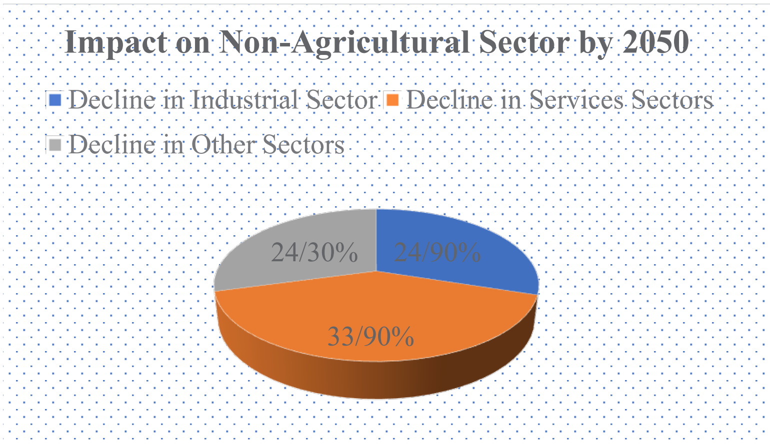

Fig 3. Impact on Non-Agricultural sector by 2050 (Source EDRI, 2021)

household's consumption budget (ERDI, 2021). According to Ethiopia Research Development Institutes (2021), the income of poor households is projected to decline by 20.4 % in the same year. Most notably, the rural poor households have lower initial per capita income expect to experiences the worst income losses. They severely suffer as they do not benefit from the higher prices for agricultural goods. At the same time, they spend a higher proportion of their income on household food expenditure. Which makes rural communities particularly vulnerable to food price changes and to the impact of climate change. Indeed, the impacts of climate change on rural household income sources vary across the different agro-ecologies of the country. In drought-prone highlands and lowland areas climate change impact tends to hurt the poor more due to their vulnerability and weak coping mechanisms. As described under figure 4, at household level the amounts of losses as result of recurrent drought are estimated to be 26.8 percent by 2050 (ERDI, 2021). In the pastoralist region, the non-poor rural households' real income will decrease by 6.8 percent, while the poor households gain 20.4 percent in 2050.

Socio-economic determinants of vulnerability

According to the Intergovernmental Panel on Climate Change (IPCC, 2007) the vulnerability and the potential impacts of climate change are determined by the exposure, sensitivity, and adaptive capacity of people and societies of rural communities. In 2007, the IPCC noted shortcomings in its definition of vulnerability, particularly in its lack of consideration of 'social vulnerability', the need to address the determinants of adaptive capacity, and the need to consider human development as an essential mediator of climate vulnerability. Building on the IPCC definition of vulnerability, the factors that affect adaptive capacity and make rural people exposed or sensitive to climate change. Mostly, adaptive capacity, exposure, and sensitivity in rural societies are shaped by non-climatic, and socio-economic factors, such as access to, and control over economic, social, and institutional resources. These resources comprise: Human capital, such as good health, skills, knowledge, and education; Social capital, including the power to influence decision-making, voting rights, and social connectedness, whether

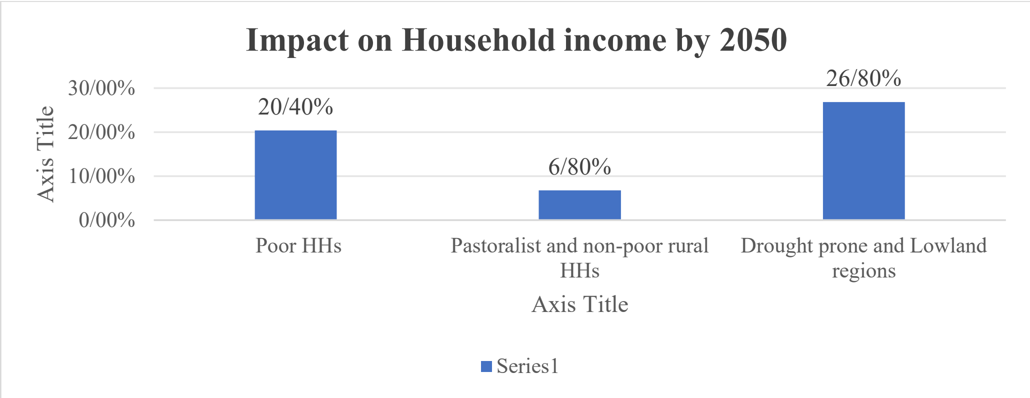

Fig 4. Impact on Household income by 2050 (source: ERDI, 2021)

to relatives, neighbors, civil society organizations, business or government agencies; Physical capital, such as shelter, farming tools, but also community infrastructure such as embankments or terraces that protect a watershed and health care facilities, for example; Natural resources, including forest, land and water; and Financial capital, such as income, savings or credit.

Socio-economic factors and institutions not only influence adaptive capacity but also exposure and sensitivity to climate-related hazards. Exposure is often considered a static factor that influences vulnerability, rather than itself being shaped through a range of political, socio-economic, and demographic processes (UN-HLCP, 2021). Changes in the number and spatial distribution of people, through population growth or decline and processes like seasonal or international migration and urbanization, can significantly change the exposure of rural populations. Availability and access to human, social and financial resources, as well as policies that support and plan for mobility, or those that attempt to restrict them or fail to plan for coming population change, are key determinants of where people live. Poor people in rural villages tend to live in hazard-prone areas, such as steep slopes or riverbanks, because they cannot afford to live in safer places, and because political, economic, and governance factors such as lack of employment and income opportunities, the absence of social services or conflict causes them to migrate to urban areas. Even among the poor, women and children can be at higher risk as they are prone to work and live in structures of lower social value and that are more poorly constructed, such as schools as compared to office buildings. Similarly, high dependence on natural resources, a key indicator of sensitivity, is linked to and shaped by economic and social structures. Policies on agriculture, land tenure, urban planning, and many others can enhance or limit people's ability to change to livelihoods that are less sensitive to climate change.

In sum UN-HLCP (UN-HLCP, 2021), the people most vulnerable to climate change are usually poor, undernourished, of poor health, live in precarious housing conditions, farm on degraded lands, have low levels of education, lack rights, have little opportunities to influence decision making, work under precarious conditions, and reside in regions, Zones, District, etc. with non-resilient health systems, limited resources and sometimes poor governance systems. Therefore, social, cultural, and political circumstances, often including inequalities and discriminatory practices, deprive them of access and basic assets. The entitlements and the institutional support need to make a living to ensure their well-being even under normal conditions. Let alone for mastering the increased and additional challenges posed by climate change. These non-climatic factors and the socio-economic context in which climatic problems occur in rural communities are likely to be as important, if not more so, than climate-related hazards themselves. In how rural communities perceive and understand the social dimension of climate change.

The social construct of climate change

According to Lindgren and Neumann (1981), society depends on climate. But what is the effect of climate anomalies on society? Which are beyond the time horizon of everyday life, and are relevant for climate change, be it human-made or due to natural processes. The slow variations appear to have had little social and economic impact in the past. Fast variations have produced irreversible social, economic, and cultural changes either by their impact on the natural environment of a society (e.g. land loss, desertification, etc.) or by demographic (rural exodus, mortality), cultural (emerging values) and economic changes (standard of living, trade patterns, the organization and location of production, agricultural yields).

Increasing carbon emissions and diminishing carbon sinks around the world underlines the 'anthropogenic' nature of climate change and reflect the ways human societies' function and change over time. Tackling climate change thus requires a broadened understanding of how human societies – and the activities that take place within them – drive climate change in different ways (UN-HLCP, 2021). While human societies necessarily interact dynamically with their environment and reshape it in response to their evolving patterns of production and consumption, the specific interactions that currently generate concerns regarding emission levels and depleted carbon sink capacities are not an inevitable outcome of development. A more sustainable development model in rural communities can enhance the capacity to meet their needs. To achieve this, it is necessary to abandon familiar indicators by which growth and prosperity are measured according to the consumption of resources, in favor of an approach that looks more directly at levels of needs satisfaction. There are well-established, long-term linkages between economic growth and resource consumption, and between economic growth and needs satisfaction. Rethinking these relationships requires an understanding of the social structures that drive climate change.

Indeed, how people provide for their material needs determines or, in general, conditions the relations that people have with each other, their social institutions, and even their prevalent ideas. Because of the importance of how people provide for their material needs. This, along with the resultant economic and livelihood relations that rural communities have, is often referred to as the basis for rural ecological well-being including lack of access to climate adaptive technologies, limited infrastructure and so on which significantly interlinked with rural communities' long-standing traditional practices in which they have their environment.

Social impacts of climate change

The social impacts of climate change are much more complicated including the risk of acute events like storms, droughts, floods, cyclical changes in precipitation, or long-term changes in temperature and sea levels. How do these trends impact rural people and societies matter the most? Most impact assessments and evaluations limit their focus to environmental and hard infrastructure impacts. However, climate change potentially affects a much wider range of sustainable social development issues – such as health, food security, employment, incomes and livelihoods, gender equality, education, housing, poverty, and mobility – either directly or indirectly (UN-HLCP, 2021). Climate change and extreme weather events affect multiple aspects of rural people's lives. The impact on health and nutrition and the ability to work and build resilient livelihood are so significant. The most important health impacts are those determined by the basic requirements for health – clean air, safe drinking water, sufficient food, and secure shelter – and are also reflected in more frequent injuries and increases in social inequities.

According to HCLP (2021) UN system analysis of the social dimensions of climate change, and determinants of what makes people vulnerable show the extent to which climate change relates to, reflects, and affects all aspects of contemporary rural societies. Climate change poses a challenge to established policy frameworks because it cuts across institutional sectors and issues that are usually addressed separately. Compartmentalizing climate change policy responses into a series of sectoral agendas, such as energy, transport, agriculture, etc., overlooks some of the key features of climate change. A fragmented response does not respond adequately to climate change. Nonetheless, addressing climate change via a sectoral, traditionally economic, cost-benefit approach is common practice in policy responses, particularly concerning the emphasis on 'end-of-pipe' methods of greenhouse gas mitigation–for example, through taxation, trade policies, and technology approaches that do not adequately reflect the social infrastructure and consequences of such methods. Major social and economic opportunities can be seized if policies comprehensively incorporate the social dimensions of climate change and strong social pillars of climate policies need to emerge to complement the traditional science and environment components.

Conclusion

Challenges to the inclusion of social dimensions of climate change are not explicitly outlined in the national climate change adaptation plan nor are they explicitly included in climate-resilient green economic development strategies. Which undermines the inclusiveness of livelihood-based social protection schemes to the climate change mitigation and adaptation action in the rural communities of the country. This has been subject to much scrutiny and diverse interpretation among researchers, policy-makers, as well as government and non-government development entities towards addressing agro-ecological and environmental concerns of rural people's lives and livelihood systems. While the ultimate successes of climate responses may currently be judged based on economic and infrastructural damage versus protection, they depend in great part on the resilience of rural people, livelihoods, health, and ecological well-being. Strategies designed and implemented without appropriate consideration of the very rural communities that interact with and depend on natural resources can undermine success in climate change action. Conversely, integrating social dimensions as a livelihood-based social protection system at all levels in the design, analysis, and implementation of sustainable development intervention in rural communities can lead to more efficient and effective climate action results on the ground. All of these require the active participation of the many and varied rural marginalized social groups within the community. Thus, the transformation of social relations with ecology to build equity, and empower success in climate change adaptation livelihood-based social protection action needs to be undertaken in the rural parts of the country.

Indeed, livelihood-based social protection within the social dimensions lens allows for a broader understanding of climate vulnerability. Directs attention to the socio-economic conditions that make rural people vulnerable in the first place, including the human and social resources, institutions, policies, and power relations that are traditionally aligned with development and poverty reduction interventions. For adaptation to be rural pro-poor for the result of enhancing resilience among the most vulnerable rural communities, addressing the socio-economic determinants of vulnerability needs to be part of adaptation strategies. At the same time, this allows accountability for climate change impacts on rural ecology, and social well-being, ranging from building the resilience of the ecological systems to sustaining social protection, and demographic factors that are critical elements of rural people's livelihood resilience.

Thus, the social dimensions of climate change, and the interplay between the social, livelihood, and rural ecology as a phenomenon. It's related to social protection policy, including the role of rural people as victims to and agents of climate change – are critical to successful climate policy, strategies, and approaches. However, to date, in Ethiopia, the human variable of the climate equation has been too frequently missing or weak. The impacts of climate change increasingly affect the daily lives of rural communities everywhere in terms of employment and livelihoods, health, housing, water, food security and nutrition, and the realization of gender equality. Impacts are expected to hit those living in poverty the hardest, partly due to their more prevalent dependency on the very natural resources affected by climate change and also because they have less capacity to protect themselves, adapt, or recuperate losses as a result of climate change-induced effects.

Therefore, climate change policies and strategies that focus on social drives can do more than ensure a climate-resilient and sustainable livelihood future for rural villagers. This also presents an opportunity to achieve more just and equitable rural societies, and advance truly sustainable economic development. So, the inclusion of social dimensions with the prospect of climate change mitigation and adaptation action has a significant ground impact on ensuring the effectiveness of livelihood-based social protection program schemes, policies, and strategies for sustaining the well-being of rural ecology across the country.

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References

Adger, W. N., Khan, S. R. & Brooks, N. (2003). Measuring and enhancing adaptive capacity, Adaptation Policy Framework: A Guide for Policies to Facilitate Adaptation to Climate Change, UNDP, in review, see http://www.undp.org/cc/apf-outline.htm.

Andrew, D., Rachel, W., Ian, M., Chris, P., Jonathan, K., & Ephraim, C. (2006). Promoting Agriculture for Social Protection or Social Protection for Agriculture: Strategic Policy and Research Issues Discussion Paper.

Andrew, B., Anthea,S., & Diana, P. (2016). Systematic Approaches to a Successful Literature Review. SAGE Publications, 2016. ISBN: 1473952808, 9781473952805.

Awoke, D., Yismaw, A., & Tarekegn, D. (2024). The effect of livelihood diversification on food security: evidence from Ethiopia, *Cogent Economics & Finance*, 12(1), 2345304, DOI: 10.1080/23322039.2024.2345304.

Brien et al. (2004). Mapping Vulnerability to Multiple Stressors: Climate Change and Globalization in India. Department of Geography, Rutgers University, 54 Joyce Kilmer Blvd., Piscataway, NJ 08854-8045 USA. Doi:10.1016/j.gloenvcha.2004.01.001.

Chambers, R. & Conway, G. (1991). Sustainable Rural Livelihoods: Practical Concepts for the 21st Century.

Conway, D. & Schipper, E.L.F. (2011). Adaptation to climate change in africa: challenges and opportunities identified from Ethiopia. *Global Environmental Change*, 21, 227-237. https://doi.org/10.1016/j.gloenvcha.2010.07.013

Daba, B., Regasa, T., & Mammo, S. (2025). Impact of climate change and variability on rural livelihood and adaptation strategies in Ethiopia: A review paper. *Front. clim* 7, 1563176. DOI:10.3389/fclim.2025.1563176.

Dendir, Z., & Semane, B. (2019). Livelihood vulnerability to climate change variability and change in different agroecological zones of Garage administrative zone, Ethiopia progress in disaster science.

Dietz, T., Shwom, R., & Whitley, C. (2020). Climate change and society, *Annual Review of Sociology*, 46, 135–158. https://dx.doi.org/10.1146/annurev-soc-121919-054614

Dorward, A., Sabates-Wheeler, R., MacAuslan, I., Buckley, C. P., Kydd, J. & Chirwa, E. (2006). Promoting Agriculture for Social Protection or Social Protection for Agriculture: Strategic Policy and Research Issues. FAC Discussion Paper, Brighton, UK: Future Agricultures Consortium.

EDRI (Ethiopian Development Research Institute). (2021). Impact of climate change on agriculture.

Farhana, Y., Atiq, U., & Saleemul, H. (2005). Vulnerability, Adaptation, and Climate Disasters: A Conceptual Overview. DOI:10.1111/j.1759-5436.2005.tb00231.x

FDRE. (2021). Climate-Resilient Green Economy Implementation and Best Practices on Climate Action in Ethiopia.

Federal Democratic Republic of Ethiopia. (2016). The path to sustainable development: Ethiopia's Climate Resilient Green Economy Strategy

Guduro,B.W. (2022). Climate change adaptation and mitigation measures in Ethiopia. ISSN Print: 2664-844X, IJAFS 2022, 4(2), 40-46. www.agriculturaljournals.com

Guhan, S. (1994). Social Security Options for Developing Countries. *International Labour Review*, 133(1), 35-53.

Hardin, G. (1968). The tragedy of the commons, *Science*, 162, 1243–1248.

Harden, A. & Thomas, J. (2010). Mixed methods and systematic reviews: Examples and emerging issues.

Hertel, T. & Lobell, D. (2014). Agricultural Adaptation to Climate Change in Rich and Poor Countries: Current Modeling Practice and Potential for Empirical Contributions. *Energy Economics*, 46, 562-575. https://doi.org/10.1016/j.eneco.2014.04.014

High-level Committee on Programmes (HLCP) of the UN System. (2021). The Social Dimensions of Climate Change.

Holzmann, R. & Jorgensen, S. (1999). Social Protection as Social Risk Management: Conceptual Underpinnings for the Social Protection Sector Strategy Paper. The World Bank, Washington DC.

IPCC. (2007). Intergovernmental panel on climate change: Fourth Assessment report.

Jesson, J., Matheson, L. and Lacey, F. (2011). Doing Your Literature Review: Traditional and Systematic Techniques. Sage, London.

K.Gërxhani, N.D. de Graaf & Raub W. (eds). (2022). Handbook of Sociological Science: Contributions to Rigorous Sociology, Cheltenham, UK and Northampton, MA, USA: Edward Elgar Publishing. DOI: 10.4337/9781789909432.00007

Kienberger, S, & Zell. (2014). ecological dimension of climate change

Klinenberg, E., Araos, M,. & Koslov, L. (2020). Sociology and the climate crisis, *Annual Review of Sociology*, 46, 649–669.

Lindgren. S, & Neumann, J. (1981). The cold and wet year 1695-a contemporary Climate Change.

Maddison, D. (2007). The Perception of and Adaptation to Climate Change in Africa. Washington DC: The World Bank. https://doi.org/10.1596/1813-9450-4308

Mesquita, P., & Bursztyn, M. (2016). Integration of social protection and climate change adaptation in Brazil, *British Food Journal*, 118(12), 3030-3043. https://doi.org/10.1108/BFJ-02-2016-0082.

MoFED (Ministry of Agriculture and Rural Development). (2021). Annual Progress Report for the Year 2020/22. Addis Ababa.

NASA's Earth Observatory. (2021). Satellite imagery, feature articles and scientific information about our home planet, with a focus on Earth's climate and environmental change.

Petticrew, M. (2001). Systematic reviews from astronomy to zoology: myths and misconceptions. DOI: 10.1136/bmj.322.7278.98

Solomon, R., Simane, B., & Zaitchik, B. F. (2021). The Impact of Climate Change on Agriculture Production in Ethiopia: Application of a Dynamic Computable General Equilibrium Model. *American Journal of Climate Change*, 10, 32-50. https://doi.org/10.4236/ajcc.2021.101003

Sinore, T & Wang, F. (2024). Impact of climate change on Agriculture and adaptation strategies in Ethiopia. A meta-analysis. https://doi.org/10.1016/j.heliyon.2024.e26103.

Slater, R., & McCord, A. (2009). Social protection, rural development, and food security: Issues paper on the role of social protection in rural development. Overseas Development Institute, London.

Trivelli, C., Vargas, S., & Clausen, J. (2017). Social protection and inclusive rural transformation.

UNDP. (2024). Scaling Up Climate Action to Achieve the Sustainable Development Goals. the Sustainable Development Goals

UNDP. (2007). Fighting Climate Change: Human solidarity in a divided world: A young people's summary of the United Nations Human Development Report 2007/2008. United Nations Development Program. UN Plaza, New York, New York, 10017, USA http://hdr.undp.org.

United Nations Environment Programme-UNEP. (2010). The Convention on Biological Diversity Year in Review 2010. Secretariat of the Convention on Biological Diversity. ISBN: 92-9225-

320-4.

UNFCCC. (2021). United Nations Framework Convention on Climate Change, article definitions for the purpose of convention.

United Nation High-level Committee on Programmes (UN-HLCP) of the UN System. (2021). The Social Dimensions of Climate Change.

World Bank. (2008). A Country Study on the Economic Impacts of Climate Change. Environment and Natural Resource Management Report No. 46946-ET, Washington DC: World Bank, Sustainable Development Department, Africa Region.

World Bank. (2024). Social protection and labor systems promote better employment, prevent income loss, and protect people against shocks and transitions.

World Bank. (2025). Rural communities vulnerability context to climate change induced disasters between 2023 - 2025.

Wolde, E. (2008). Global Climate Change and Its Economic Impact on Sub-Saharan Africa: Simulation of a Computable General Equilibrium Model for Ethiopia. MSc. Thesis, Oslo: Department of Economics, University of Oslo

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