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مجلة علمية محكمة نصف سنوية

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كلمة العدد :

الحمد لله الذي علّم بالقلم، علّم الإنسان ما لم يعلم، والصلاة والسلام على سيدنا محمد وعلى آله وصحبه أجمعين.

يسرّ هيئة تحرير مجلة جامعة المصطفى للعلوم الهندسية أن تقدّم لقرّائها الكرام العدد الثاني من المجلة، استمرارًا لمسيرتها العلمية الرامية إلى دعم البحث الرصين وتعزيز ثقافة الابتكار في مختلف التخصصات الهندسية.

إنّ هذا العدد يأتي ثمرة جهود علمية متميزة لعدد من الباحثين والأكاديميين الذين أسهموا بأبحاثهم الأصيلة في مجالات متعددة، تعكس التقدّم المعرفي والتطوّر التقني المتسارع في العلوم الهندسية. وقد حرصت هيئة التحرير على اعتماد أعلى معايير التحكيم العلمي، لضمان جودة البحوث المنشورة وأصالتها وقيمتها العلمية.

وإيمانًا منّا بأهمية التكامل بين الجانب النظري والتطبيقي، فقد تضمّن هذا العدد دراسات تسهم في معالجة مشكلات واقعية وتقديم حلول هندسية مبتكرة، بما يخدم المجتمع ويعزز التنمية المستدامة.

ونحن إذ نضع هذا العدد بين أيديكم، نأمل أن يكون إضافة علمية نافعة، ومنبرًا يُثري الحوار الأكاديمي، ويحفّز الباحثين وطلبة الدراسات العليا على مزيد من العطاء والإبداع.

نسأل الله التوفيق والسداد، وأن يبارك في الجهود المبذولة لخدمة العلم والمعرفة.

هيئة التحرير

مجلة جامعة المصطفى للعلوم الهندسية

هيئة التحرير :

قواعد النشر في المجلة :

1- تتخصص المجلة بنشر البحوث ذات التخصصات العلمية والهندسية .

2- تعرض البحوث المقدمة للمجلة على هيئة التحرير؛ لبيان ملاءمتها ويحق لهيئة التحرير أن تعتذر عن قبول البحث .

3- يتم عرض البحث مسبقاً على لجنة السلامة اللغوية ولجنة السلامة الفكرية .

4- تلتزم هيئة التحرير بإرسال البحوث إلى خبراء علميين من الاختصاص نفسه عدد (3) وفي حالة الرفض من أحدهم يرسل إلى خبير ثالث لغرض الترجيح .

5- تلتزم هيئة التحرير بعدم الكشف عن أسماء المحكّمين ، لضمان سرية التحكيم ولرفع، الرصانة العلمية وكذلك تكون المعلومات الخاصة بهوية الباحث في الصفحة الأولى من البحث فقط . وأن يلتزم الباحث بعدم الإشارة إلى هويته أومكان عمله في ثنايا البحث .

6- تكون حقوق الطبع للبحث ملكاً للمجلة عند قبوله للنشر ولا يحق النقل والاقتباس عنه إلا بعد الإشارة إلى المجلة .

7- لا يجوز نشر أكثر من بحث للباحث في العدد الواحد .

8- تحتفظ هيئة التحرير بحق أولوية النشر للبحوث مع مراعاة التنويع في النشر بحسب المحاور المعتمدة .

9- ما ينشر في المجلة من بحوث ودراسات تعبّر عن رأي أصحابها ولا تعبر بالضرورة عن وجهة نظر هيئة تحرير المجلة أو وجهة نظر الكلية .

شروط النشر :

1- قبول البحوث المقدمة للنشر باللغة الانكليزية .
2- يقدم الباحث ثلاث نسخ من البحث مطبوعة على (A4) ويضم ملخصاً باللغتين العربية والانكليزية وأن لا يزيد الملخص عن 150 كلمة .
3- يكون الطبع ببرنامج Microsoft Word ونوع الخط Simplified Arabic بالنسبة للبحث باللغة العربية أما البحوث باللغة الانكليزية فيكون نوع الخط Times new Roman.
4- يكون حجم الخط (14) للمتن و (12) للهوامش و (16) للعنوان الرئيس و (15) للعنوان الفرعي .
5- أن لا يزيد عدد صفحات البحث عن (25) صفحة .
6- يتعهد الباحث أن يكون البحث غير مقدم للنشر مسبقاً إلى جهة أخرى .
7- تقديم نسخة الكترونية من البحث على قرص (CD) بعد إجراء التعديلات المطلوبة من المحكمين .
8- ترفق السيرة الذاتية للباحث مع البحث .
9- يكون التوثيق العلمي للهوامش على وفق الآتي :
أ- كتابة الهامش في متن البحث في الصيغة الاتية (اسم الملف،السنة،الصفحة).
ب- كتابة الهامش اسفل الصفحة وفق الاتي : (اسم المؤلف ، عنوان الكتاب ،دار الطبع ، بلد الطبع ، السنة ، الطبعة ، ص) .

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المحتويات

بحوث المجلة

Integrated water resources management through linking sustainable irrigation and drainage systems and achieving food security

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Abstract

Integrated Water Resources Management (IWRM) is a modern approach aimed at using water sustainably and efficiently, taking into account the integration between various sectors such as agriculture, industry, environment, and society. In the agricultural sector, improving water use efficiency through the integration of sustainable irrigation systems and efficient drainage and drainage is the cornerstone of achieving food security, especially in areas suffering from water scarcity or land degradation. Integrated management relies on comprehensive planning that considers all aspects of water use, including the quantity of water available, the timing of its use, and the appropriate distribution methods for each crop. The most prominent sustainable irrigation systems that contribute to this management include drip irrigation, which delivers water directly to the root zone while reducing waste; sprinkler irrigation, which simulates rainfall and provides uniform distribution; and improved surface irrigation, which reduces waste and optimizes the use of heavy soils. Sustainable drainage and drainage systems aim to remove excess water and prevent soil salinization, thus maintaining soil fertility and increasing crop productivity. Integrating sustainable irrigation and drainage is the basis for achieving water use efficiency and improving agricultural

production. By implementing these systems, water loss can be reduced, soil moisture levels improved, salt accumulation prevented, and agricultural productivity increased sustainably. Reusing treated wastewater also provides an additional opportunity to save water and reduce pressure on freshwater resources, enhancing sustainable food production. This management is closely linked to achieving food security, which encompasses four dimensions: food availability, food access, food stability, and proper food utilization. Improved water management leads to increased food production, sufficient food supply for the population, and equitable distribution, while preserving the sustainability of natural resources. Linking sustainable irrigation and drainage systems within the framework of integrated water resources management represents an effective strategy for addressing water scarcity and achieving food security. It ensures optimal use of resources, protects the agricultural environment, and improves crop productivity, contributing to the sustainability of agriculture and the provision of food for current and future generations. This approach provides an integrated model that can be applied in multiple regions facing similar challenges, making it one of the key solutions for achieving sustainable food security in light of increasing pressure on water resources.

Keywords: Integrated Water Resources Management, Sustainable Irrigation Systems, Agricultural Drainage, Water Use Efficiency, Food Security

1.1 Introduction

Water resources are the cornerstone of achieving sustainable development across various economic and social sectors, most notably the agricultural sector, which represents the largest consumer of water globally. With increasing population pressures, expanding agricultural and industrial activity, and the intensifying effects of climate change, there is an urgent need to adopt integrated water resources management (IWRM). IWRM is a scientific and systematic approach aimed at optimal water use and achieving a balance between meeting current needs and protecting this vital resource for future generations. IWRM is based on the principle of viewing water as a single, interconnected system, integrating its various surface and groundwater sources and various uses within a comprehensive strategic framework that achieves both efficiency and sustainability. In this context, linking irrigation and drainage systems represents one of the most important practical aspects of IWRM. IWRM aims to achieve a balance between efficient water use in irrigation and the removal of excess water to maintain soil fertility and prevent soil degradation. Irrigation is the primary means of supplying agricultural crops with water, but its overuse or mismanagement leads to serious problems such as soil salinization and rising groundwater levels. Hence, the importance of drainage systems, which work to dispose of excess water and remove harmful salts, thus maintaining agricultural productivity and extending the life of arable land. The integration of these two systems enables the recycling of drained water and its use for irrigation purposes after treatment, which increases the efficiency of water resource utilization and reduces waste. Achieving food security is the ultimate goal of this approach, as food security is linked to a society's ability to provide sufficient, safe, and sustainable food in the face of rapid population growth, climate change, and resource fluctuations. Integrated water resource management, through improving irrigation systems and developing sustainable drainage technologies, contributes to increasing unit water productivity (i.e., the amount of crop produced per cubic meter of water) and enables the cultivation of strategic crops such as grains and vegetables in limited water conditions. This management also enables adaptation to climate change through water harvesting techniques, the use of drought-resistant agricultural varieties, and the reuse of treated water, ensuring stable agricultural production and long-term food availability. Adopting this integrated approach is not limited to the technical aspect alone. It also requires supportive government policies, close cooperation between various sectors, and active community participation. Successful integrated water resources management requires the development of comprehensive strategic plans, the development of irrigation and drainage infrastructure, and the implementation of modern methods such as smart irrigation and digital monitoring of water distribution. Through these efforts, it becomes possible to achieve rational water use, preserve soil fertility, reduce pollution, and ensure sustainable food production that achieves self-sufficiency and enhances national and regional food security. Thus, integrated water resources management, based on the integration of sustainable irrigation and drainage systems, represents a practical and strategic approach to addressing the challenges of water scarcity and the pressures of increasing demand. It is the cornerstone of building a resilient agricultural system capable of continuing to meet present and future needs.

1.2 The Research Problem

Most countries, particularly in arid and semi-arid regions, face a growing water crisis due to increasing demand for water caused by rapid population growth, agricultural expansion, and climate change, which is leading to the decline of surface and groundwater resources.

The agricultural sector is the largest consumer of water, as inefficient traditional irrigation practices waste large quantities of water, raise groundwater levels, and lead to soil salinization. The lack of integration between irrigation and drainage systems also leads to decreased agricultural land productivity and declining food security. Hence, the research problem arises from the absence of integrated water resource management that effectively links sustainable irrigation and drainage systems to ensure optimal water use, soil conservation, and food security.

1.3 The Importance of the Research

The importance of this research stems from its addressing one of the most pressing strategic challenges of our time: water scarcity and its impact on food security. The research provides a scientific framework for adopting policies and strategies that enable integrated water resource management, ensuring increased water use efficiency, reducing waste, preserving agricultural land fertility, and achieving sustainable food production. The study also gains importance from the potential application of its findings in developing countries that suffer from limited water resources and high rates of desertification.

1.4 Research Objectives

The research aims to:

1 -Analyze the reality of water resource management in light of environmental and economic challenges.

2 -Clarifying the role of integrated irrigation and drainage systems in improving water use efficiency.

3 -Reviewing sustainable drainage techniques and methods and their role in reducing soil salinization.

4 -Highlighting the impact of integrated water management on enhancing food security and achieving agricultural sustainability.

1.5 Research Methodology

The research relies on a descriptive and analytical approach, collecting data from previous studies, international reports, and agricultural statistics, and analyzing them to uncover shortcomings in water resource management and evaluate the role of sustainable irrigation and drainage systems in improving agricultural production. A comparative approach is also used to compare the experiences of different countries in implementing integrated water management.

1.6 Research Hypothesis

Main Hypothesis: Implementing integrated water resource management based on linking sustainable irrigation and drainage systems leads to increased water use efficiency and achieving food security.

Sub-Hypotheses:

1 -Improving drainage techniques reduces soil salinization and increases productivity.

2 -Modern irrigation systems contribute to reducing water loss and improving water quality.

1.7 Previous Studies

1-GWP (Global Water Partnership), 2010

o Title: Integrated Water Resources Management in Practice

o The study addressed the concept of integrated water resources management as a tool for achieving water sustainability through coordinating surface and groundwater management and integrating the agriculture and energy sectors.

o It focused on the importance of involving farmers and stakeholders in water management to achieve higher irrigation efficiency.

2-Abdelaziz, M. (2018). "Integrated Water Resources Management in the Arab World"

o A case study of several Arab countries (Egypt, Morocco, Jordan).

o It highlighted the need to integrate irrigation policies with drainage policies to reduce soil salinization and maintain the fertility of agricultural land.

3-Hassan, S. (2020). "Integrating Irrigation and Drainage Systems to Achieve Agricultural Sustainability in the Nile Delta"

o An Egyptian study focused on the use of covered drainage in conjunction with improved field irrigation systems.
o Results: A 25% reduction in soil salinity and an increase in wheat and rice productivity.

Integrated water resources management (IWRM) is a strategic approach aimed at achieving optimal water use through comprehensive planning and coordination among various sectors related to water resources, such as agriculture, industry, environment, and society. This concept is based on the principle that water is a limited and vital resource that requires balanced management to ensure meeting present needs without compromising the rights of future generations. With increasing global challenges such as rapid population growth, climate change, and the expansion of agricultural and industrial activity, the implementation of integrated management has become an urgent necessity to ensure resource sustainability and achieve comprehensive development. IWRM focuses on rationalizing consumption, protecting surface and groundwater resources, and improving water use efficiency in various sectors, particularly in the agricultural sector, which is the largest consumer of water. IWRM also aims to reduce pollution, minimize waste, and enhance local community participation in decision-making, contributing to achieving water equity between regions and users. By integrating modern irrigation methods and sustainable drainage technologies, IWRM provides an effective framework for maintaining soil fertility and increasing agricultural production, thereby contributing to enhancing food security. This comprehensive approach represents the cornerstone for achieving sustainable development, as it combines economic efficiency, environmental conservation, and ensuring the availability of water for future generations (FAO, 2017: 65).

2.1: The Concept of Integrated Water Resources Management

Integrated Water Resources Management (IWRM) is a strategic approach aimed at comprehensively and interconnectedly planning, developing, and managing water resources to ensure sustainable water use and achieve a balance between economic, social, and environmental needs. This concept considers water a limited and vital resource affected by natural and human factors, which requires coordinating policies and plans across all sectors (agricultural, industrial, urban, and environmental) to achieve maximum efficiency in its use, while preserving the rights of future generations.

2.2: Principles of Integrated Water Resources Management

Integrated water resources management is based on a set of fundamental principles endorsed by international organizations such as the Global Water Partnership (GWP), most notably:

1-The holistic unity of the water resource: viewing surface water, groundwater, and reused water as a single, interconnected system, integrating environmental, economic, and social aspects.

2-Community Participation: involving all stakeholders (governments, farmers, industries, and civil society) in the planning and decision-making process to ensure sustainable solutions.

3-Considering water as an economic and social resource. Recognizing its economic value and the need to price it to encourage rational consumption, while ensuring everyone's right to clean water.

4-Balancing development and environmental conservation. Achieving optimal water use to support agricultural and industrial growth without harming ecosystems or depleting resources.

5-Integrating policies and sectors. Coordinating water plans with energy, agriculture, health, and urban planning policies to ensure coordinated and sustainable management. (FAO, 2017: 65)

6-Equity and efficiency. Distributing water resources equitably among users and regions, while increasing water use efficiency at all stages, from withdrawal to

2.4.1 Types of irrigation systems (drip, sprinkler, and surface irrigation).

Sustainable irrigation systems are among the most important means of achieving optimal use of water resources in agriculture. They directly contribute to increasing crop productivity, reducing water loss, and protecting soil from degradation. The most prominent of these systems are drip irrigation, sprinkler irrigation, and surface irrigation. These systems differ in their method of delivering water to plants and their efficiency, but they all aim to achieve sustainable water resources. (Al-Sayyad, Muhammad, 2016: 56)

1- Drip Irrigation: Drip irrigation is a system that delivers water directly to the plant's root zone via a network of precise pipes and valves. It is considered one of the most water-efficient irrigation systems. This method reduces evaporation and runoff, allowing for the use of smaller amounts of water compared to traditional methods. Drip irrigation also improves nutrient uptake and limits weed growth, thus increasing crop yields. This system is particularly used for horticultural crops, fruit trees, and vegetables. Although its initial cost is higher than traditional methods, the agricultural yield and water efficiency make it an economically and environmentally sustainable option in the long term.

2 -Sprinkler irrigation Sprinkler irrigation relies on distributing water in the form of a spray that simulates rain using sprinklers or rotating pivots, allowing for uniform coverage of the cultivated area. (Al-Sayyad, Muhammad, 2016: 56) This system helps reduce erosion and improves soil aeration around plants. Fertilizers can also be added to the irrigation water to provide balanced plant nutrition. Sprinkler irrigation is suitable for field crops, pastures, and lands with light or sandy soil. It is less expensive than drip irrigation in terms of initial installation, but it requires careful monitoring to ensure that water is not wasted due to wind or evaporation. (Hussein, Ali, 2014: 45)

3 -Improved surface irrigation Improved surface irrigation is an update to traditional flood irrigation. It involves carefully leveling the land and creating controlled channels to direct water to plants in a systematic manner. This system reduces water loss due to seepage or random runoff, and also reduces operating and maintenance costs compared to older methods. Improved surface irrigation is used to grow cereals, rice, and crops on heavy or low-slope soils. Although less efficient than drip or sprinkler irrigation, it remains an economical option suitable for areas with moderate water availability and suitable terrain. (Hussein, Ali 2014: 45)

4 -Bubble irrigation

Bubble irrigation can be defined as an irrigation system that combines drip irrigation and sprinkler irrigation. This method relies on injecting air into water pipes or tanks, thereby increasing the oxygen content in the water by approximately 150% and, consequently, increasing its content in the soil. This helps eliminate harmful bacteria and improve the soil. This system uses a bubbler device to regulate the flow of air into the water pipes before watering. (Abdullah, Khaled 2014: 23)

2.4.2: Water use efficiency and its impact on production.

Water use efficiency is one of the most important elements in sustainable water resource management, especially in the agricultural sector, which consumes the largest proportion of available water. Water use efficiency refers to the ability of an agricultural system to achieve the highest possible crop yield per unit of water used, whether in irrigation or in drainage and treatment processes. The higher the efficiency, the lower the amount of water wasted and the better the soil fertility, which directly contributes to enhancing agricultural productivity and food security. Water use efficiency impacts production in several ways: First, by improving plant water nutrition, as it ensures proper water distribution reaches plant roots without loss due to evaporation or surface runoff. Second, by reducing soil salinization and degradation resulting from over-irrigation, which maintains soil fertility and prolongs its productive life. Third, implementing sustainable irrigation systems such as drip or sprinkler irrigation allows for a significant reduction in water loss, sometimes by 40–50% compared to conventional irrigation. This means more efficient use of water to increase crop yields without the need to increase the amount of water consumed. (Al-Faris, Sami, 2017: 63) In addition, improving water use efficiency contributes to reducing the operational costs of energy and labor associated with irrigation, and helps alleviate pressure on available water resources, especially in arid and semi-arid regions. This factor is considered vital in facing the challenges of water scarcity and climate change, as it allows agriculture to continue without harming the resource or the surrounding environment.

2.5: Sustainable Drainage Systems

Sustainable drainage systems are an essential part of water resource management, aiming to drain excess water from the soil in a way that preserves its fertility and prevents salinization. Sustainable drainage is an effective tool for maintaining water balance in agricultural lands, contributing to improved crop growth and increased productivity without harming the environment. It also enhances the integration of irrigation and drainage and enables the reuse of drained water, supporting the optimal use of water resources and ensuring the sustainability of agricultural production and food security in the long term. (Al-Shami, Youssef, 2015: 73)

o Prevents water accumulation around the roots and reduces soil salinization.

o Maintains soil moisture at a level suitable for crop growth.

• Advantages: Reduces evaporation, increases productivity, and protects the soil from cracking or deterioration of its fertility.

• Limitations: High initial cost and difficulty in maintaining it in some areas.

3-Biological drainage: Relies on the use of deep-rooted plants or vegetation to naturally draw excess water from the soil.

Importance:

o Contributes to reducing excess water levels and preventing soil salinization. (Al-Masry, Sameh: 2019: 43)

o Promotes environmental sustainability and reduces the need for expensive infrastructure.

- ❖ Advantages: Environmentally friendly, maintains soil fertility.
- ❖ Limitations: Drainage is slower than mechanical methods, and depends on the plant type and climatic conditions.

The role of drainage in preventing salinization

Salinity is one of the biggest challenges facing agricultural lands, especially in arid and semi-arid regions. Agricultural drainage contributes to:

- ❖ Removing excess salts from the soil And prevent its accumulation on the surface.
- ❖ Improve soil aeration and stimulate root growth.

- Increase crop productivity by providing a suitable agricultural environment.

1 -Wastewater Reuse Techniques.

Wastewater reuse is an effective solution to address water scarcity and ensure the sustainability of water resources in agriculture, industry, and urban areas. It allows previously consumed water to be reused after treatment and purification, making it suitable for reuse. This reduces pressure on freshwater resources, contributes to environmental conservation, and increases agricultural productivity. This process relies on advanced technologies for treating wastewater and removing impurities and pollutants, ensuring the health and nutritional safety of plants or industrial use. (Saleh, Nasser 2016: 55)

1 -Biological Treatment

This technology relies on microorganisms such as bacteria and algae to decompose organic matter in wastewater.

• Advantages:

o Effective in removing organic matter and biological pollutants. (Ibrahim, Mohammed: 8 201: 41)

o Relatively low operating costs compared to chemical methods.

• Uses: Irrigation of non-sensitive crops or reuse of water for industrial purposes.

2 -Chemical Treatment

Involves adding chemicals such as chlorine or oxygen to treat wastewater and eliminate germs and pollutants.

• Advantages:

- ❖ Fast and effective sterilization and elimination of harmful microorganisms.
- ❖ Suitable for applications requiring high-quality water.

•Limitations: May leave chemical residues that require special management before agricultural use.

3 -Sand Filtration and Filtering

Water is passed through layers of sand or advanced filters to remove solids and suspended matter.

Food security is one of the most significant challenges facing societies worldwide, ensuring the continuous availability of sufficient and nutritious food for all individuals. This concept relates not only to agricultural production, but also to the management of natural resources, particularly water and soil, to ensure that the nutritional needs of the population are met. Food security also encompasses the ability to access food economically and physically, ensuring its proper use to achieve healthy nutrition, and ensuring long-term stability in food availability. In light of rapid population growth, climate change, water scarcity, and environmental degradation, achieving food security has become a strategic goal closely linked to the management and sustainability of natural resources to ensure societal well-being and stability. [

3.2: The relationship between food security and water management.

Water is one of the most important natural resources needed to achieve food security, as it is an essential component of food production for both plant and animal populations. Without sufficient and quality water, crops cannot be grown or livestock raised sustainably, threatening countries' ability to feed their populations. Hence, the close relationship between water resource management and food security becomes apparent, as food security depends on the availability, efficient use, and sustainability of water.

The Role of Water in Food Security: Water plays a pivotal role in food production, as agricultural irrigation depends on providing sufficient quantities of water at the appropriate time for crop growth. The agricultural sector consumes approximately 70% of the world's freshwater, making it the largest consumer of this vital resource. Food security also depends on water for livestock production, as animal husbandry requires water for drinking, farm cleaning, and fodder production. Any shortage or mismanagement of water resources leads to reduced agricultural production, increased food prices, and threats to food stability, especially in arid and semi-arid regions. (Hamza, Adel: 5 201:50)

Water Management for Food Security Water management involves developing plans and strategies to ensure optimal use of water resources, reduce losses, and maintain water quality. This management includes several elements:

1-Improving irrigation systems: Using drip, sprinkler, or smart irrigation techniques increases water efficiency and reduces losses.

2-Sustainable drainage and agricultural irrigation: Removing excess water and reducing salinization maintains soil fertility and increases crop productivity.

3-Reusing wastewater: Treating used water and reusing it for irrigation contributes to providing additional resources and reduces pressure on freshwater. (Hamza, Adel: 5 201:50)

4-Water storage and harvesting: Building dams and reservoirs to collect rainwater ensures its availability during droughts.

Challenges in the relationship between water and food security This relationship faces several challenges, including water scarcity, climate change, degradation of agricultural land, and increasing population demand for food. Drought and erratic rainfall lead to reduced agricultural production, while over-irrigation and mismanagement of water resources lead to soil salinization and groundwater depletion. Therefore, achieving sustainable food security requires integrated water management that takes into account agricultural, environmental, and economic dimensions. (Ibrahim, Muhammad: 8 201:41)

3.3 Application Framework (Case Study)

To demonstrate the practical application of IWRM concepts, a case study can be selected from a region or country facing water scarcity and its impact on food security. This study aims to analyze how to improve agricultural water use by combining sustainable irrigation systems with efficient drainage and drainage to achieve higher productivity and provide sufficient food for the population.

1 -Selecting the Region: Semi-arid regions or those experiencing erratic rainfall and high temperatures are suitable for conducting this study. For example:

•The Nile River Basin in Egypt and Sudan: These regions face increasing pressure on water resources due to population growth and climate change, which impacts food security.

•Agricultural lands in Iraq or Morocco: These lands suffer from salinization problems, high groundwater levels in some areas, and scarce water availability for irrigation, which reduces agricultural productivity.

Selecting these regions allows for a realistic analysis of the current situation and an assessment of the impact of IWRM implementation on food production and resource sustainability. (Hamza, Adel: 5 201:50)

2 -Analyzing water use data and irrigation and drainage systems. The analysis includes collecting accurate data on:

•Water sources: the amount of surface and groundwater used, water quality, and its distribution by agricultural season.

•Irrigation systems: identifying the type of irrigation systems used, such as drip irrigation, sprinkler irrigation, and improved surface irrigation, and evaluating their efficiency in delivering water and reducing waste.

•Drainage systems (drainage): analyzing the effectiveness of drainage in removing excess water, reducing salinization, and maintaining soil fertility.

•Agricultural production: evaluating the production levels of different crops, compared to the amount of water used, and identifying gaps resulting from mismanagement of resources. (Ibrahim, Mohammed: 8 201:41)

3 -Evaluating the effectiveness of integrated management

After analyzing the data, the impact of integrated management on food security is evaluated through a set of indicators:

- Water use efficiency: measuring the amount of water used per unit of production and analyzing the improvement of water distribution among crops.
- Soil quality improvement: evaluating the role of drainage and drainage systems in reducing salinity and increasing soil fertility.
- Increased productivity: Monitoring changes in crop productivity after implementing sustainable irrigation and efficient drainage techniques.
- Water reuse: Studying the possibility of using treated wastewater to irrigate crops, reducing pressure on freshwater resources and increasing production sustainability.

Expected outcomes

Expected outcomes from implementing integrated management include:

- Improving water use efficiency and reducing waste, allowing water to be allocated to more crops or other uses.
- Improving soil fertility and reducing salinization, enhancing long-term productivity.
- Increasing agricultural production and food security, ensuring sufficient food for the population.

• Providing a practical model that can be replicated in other regions facing similar challenges.

Conclusions and Recommendations

Integrated water resources management (IWRM) is a vital approach to ensuring optimal water use in agriculture and achieving sustainable food security. Combining sustainable irrigation systems with efficient drainage and drainage improves crop productivity, maintains soil fertility, and rationalizes water consumption amid increasing water scarcity. The study, along with the theoretical and applied frameworks, demonstrates that the integration of these systems represents a practical solution to address water, environmental, and economic challenges and enhances the resilience of agricultural communities to climate variability and population growth.

Conclusions

1 -Water efficiency is a key component of food security: The use of modern irrigation systems such as drip and sprinkler systems, along with sustainable drainage, increases water use efficiency and reduces losses, thus increasing crop productivity.

2-Drainage and drainage maintain soil fertility: Sustainable drainage of excess water prevents salinization and agricultural degradation, ensuring the long-term sustainability of productive lands.

3 -Integrating irrigation and drainage increases sustainability: Combining advanced irrigation technologies with efficient drainage systems enhances the ability to produce sufficient food without depleting water resources.

4 -Reusing wastewater is a sustainable opportunity: Treating and reusing agricultural wastewater provides additional water sources and reduces pressure on freshwater.

5 -Community participation and effective policies are essential: Involving farmers and decision-makers in planning and implementation ensures sustainable and effective policy implementation

Recommendations

1 -Widespread implementation of sustainable irrigation systems: Encourage the use of drip and sprinkler irrigation and smart water control in all agricultural areas.

2 -Developing drainage and drainage infrastructure: Improving drainage networks and treating excess water to ensure water balance and protect soil from salinization.

3 -Reusing wastewater: Investing in water treatment technologies for safe and effective reuse in agricultural irrigation.

4 -Enhancing training and awareness: Disseminating training programs for farmers on integrated water management, irrigation rationalization, and the importance of sustainable drainage.

5 -Integrating agricultural and water policies: Developing integrated national plans that combine water management, agricultural production, and environmental protection to achieve sustainable food security.

6 -Research and Innovation: Supporting studies and research to develop new technologies to increase water efficiency and address the challenges of water scarcity in the face of climate change.

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Thermal Performance Enhancement Techniques of Silicon-Based Solar Panels-Review Article

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ABSTRACT

Thermal management is one such critical parameter dominating the electrical efficiency and reliability of silicon-based photovoltaic (PV) modules, as higher operating temperatures impair the power output and accelerate the degradation rate and cost of energy for PV cells. This review critically summarizes contemporary research trends and literature on the augmentation and enhancement of thermal management for silicon-based PV modules through passive, active, material-based, and combination or innovative approaches involving the integration of photovoltaic and thermal management concepts for silicon-based PV modules. It is clear from the review that passive methods for temperature reduction with reduced cost and system complexities can be achieved to a small extent compared to active methods that promote higher efficiencies and greater system complexities with higher energy requirements. Research on material and nano-technologies can offer improvements for localized heat removal and evacuation with minimal system design and modification interventions on silicon-based PV modules, while combination approaches involving solar PV and solar thermal technologies offer the greatest overall energy conversion efficiency.

Keywords: photovoltaic–thermal (PVT), silicon photovoltaic, phase change materials

INTRODUCTION

The search of the sustainable sources of energy has been escalating over the last few years, and this has been mainly caused by the urgent need to solve the problems of climate change and environmental degradation. Solar energy is one of the technologies of renewable energy that has been the leader in technological advancement, due to its abundance and cost reduction related to solar photovoltaic (PV) technology. Solar panels made of silicon (especially) are the main engine of the existing solar market as they illustrate a considerable portion because of the prevalence and productivity. But there are still issues with their thermal performance which can reduce their overall efficiency under high temperature environments. Improving the thermal characteristics of these panels is therefore not only technically crucial, but it is also central to whether solar energy can become a mainstream source of power or not. The literature has covered numerous thermal enhancement methods, based around such topics as cooling methods, material innovations, and hybrid systems, and aimed at addressing the deficiencies which accompany silicon solar panels in high thermal load conditions [1][2]. Although much literature has clarified the processes of thermal degradation and provided new approaches to the problem, the literature has gaps in knowledge. Indicatively, active cooling systems, such as the use of liquid cooling and phase change materials, have had encouraging results, but the issue of scalability and affordability of such systems in business contexts is yet to be substantiated with empirical research [3][4]. Moreover, incorporation of new materials to improve thermal dissipation including nanofluids and novel coatings is also exciting but the long term performance of such materials has been little evaluated [5][6][7]. In addition, hybrid systems using solar thermal systems and photovoltaic are also receiving growing interest as a two-fold method of maximizing the output of energy. It was successfully shown that these systems may successfully utilize both electrical and thermal energy, however, there are no extensive reviews which may provide the consolidation of findings of various experimental systems and geographical conditions [8] [9]. Moreover, although there are theoretical models used to predict the effect of temperature on the losses of silicon solar cells, the experimental evidence to support the models in diverse climatic conditions is lacking [10] [11]. Currently, most of the current literature either dwells on experimental proofs of certain cooling methods or speculative improvement of material science, and there exists a need to unify the studies between these realms [12] [13]. The necessity of the complex approach that will take into account the technological improvements and practical implementation in the various environmental conditions is gaining momentum [14] [15]. Therefore, this review aims at summarizing the existing body of knowledge on thermal performance improvement methods in silicon based solar panels. Through critical review of the available literature and the highlighting of gaps in current research, the aim of the review is to shed light on avenues of future research that could lead to more effective and cost effective solar power solutions which can eventually help in achieving the goal of energy transition into sustainability [16][17][18][19][20]. In brief, a literature about thermal performance improvements of silicon solar panels shows a diverse yet disjointed terrain. With the further development of research, it is paramount to promote interdisciplinary partnerships, which are able to meet the multidimensional issues of the nexus of engineering, material science, and market dynamics [21][22][23]. The identified gaps as well as the focus on the integrative perspective presented by the review establish the environment in which the further research and development are to be carried out in the framework of solar thermal management strategies [24][25][26]. Finally, the result of this review will not only contribute to the development of academic knowledge but can also appeal to the industry stakeholders who are interested in practical solutions to the problem of improving the efficiency of solar energy [24][27][28] [29] [30] [31] [32] [33] [34] [35] [36] [37][38] [39].

REVIEW OF LITERATURE

The search of the enhancement of thermal performance of silicon-based solar panels has been developing considerably throughout the last few decades, characterized by different innovative approaches and efficiency rates to grow. Initial investigations were mainly passive type cooling, and it was shown that heating of the air flowing over solar panels could be used to reduce solar heating, which is harmful to the performance[1][2]. With the development of research, the use of sophisticated materials, including thermally conductive polymers, phase change materials, etc., became more prominent, which emphasized significant advances in thermal regulation [3][4]. The above innovations highlighted the dire necessity of the development of integrated thermal management systems that are not only beneficial in performance, but also increase the life of solar modules. However, over the past 20 years, focus has been directed on active cooling systems, including water cooling systems and hybrid photovoltaic-thermal (PVT) systems. These systems have been reported to make a huge contribution to the energy eco-friendliness by producing both thermal power and electricity simultaneously [5][6]. However, in the recent developments, even nanotechnology has also been used, with innovative coatings that facilitate better heat dissipation and reduce degradation of solar panels to a minimum [7][8]. Moreover, recent research has started to highlight the effects that the physical environment has on thermal performance, with the implication that location and climatic conditions should be considered when selecting and designing cooling methods [9][10]. The historical evolution of these methods shows an obvious tendency to more complex thermal management systems that consider not only short-term performance but also more global sustainability objectives. Therefore, the literature has been an indication of a booming industry that has yet to innovate in line with the increased desire of an efficient solar energy solution and current studies are ensuring more improvements in thermal performance in line with the current research [11][12]. In the end, this review summarizes the dynamic process of development of technologies and the environment in the optimization of silicon-based solar panels. The studies about optimization of thermal characteristics of silicon-based solar panels also enable outlining various innovative approaches and their effects on energy efficiency. The utilization of cooling technologies to counter the adverse implications of increased operating temperatures on the efficiency of solar panels is also one of the most conspicuous topics of the literature. Different literature papers have shown that passive cooling, like the incorporation of phase change materials, can considerably enhance the performance on the basis of sustaining optimum temperature limits, to gain the maximum energy output[1][2]. In addition, another area for the enhancement of thermal management is the investigation of advanced surface materials. Some hydrophobic and reflective surfaces might be useful in reducing the amount of solar heat received and enhancing the rate of energy conversion processes [3]. More recent studies verify that, after enhancing thermal efficiency, such surfaces can be beneficial for prolonging the life and reducing the maintenance needs of solar panels as well [4][5]. Another significant area that needs attention is the structural modification made on silicon panels for enhancing heat dissipation process efficiency. Incorporating high thermal conductivity materials has proved to be fruitful for enhancing heat transfer from silicon surfaces that are highly necessary for hot periods [6][7]. Some feasible methods for enhancing thermal efficiency can be found in the literature with regard to fin and heat sink integration to counterbalance the possible loss in solar panel structure design efficiency as well [8]. All the above investigations proved that finding a solution for silicon solar panels for enhancing efficiency is a complex task. The current study explains the significance of using multidisciplinary approaches because the research indicates that the thermal management improvements not only enhance the energy efficiency but may also reduce the overall cost of the solar energy system [9][10]. This has been brought about by various methodological techniques that have had a great impact on the comprehension of thermal performance enhancement techniques on the silicon-based solar panels to add to a variety of literature. Experimental research, including the one by Talukder M.Jet al. [1] and Badran G et al. [2], gives a background knowledge in terms of the behaviors of materials in different conditions, the effectiveness of the modern cooling methods, and the effect of the surface alterations. The studies have been carried out in many cases using controlled laboratory conditions, whereby the results of the study are quantifiable and used in practice. On the other hand, simulation models, such as those in I. Subedi et al., [3] and Choubani K et al., [4] take advantage of computer modeling to estimate thermal characteristics when the system is operated under various operating conditions. The theoretical structures enable the discovery of design changes without the limitations of the physical prototypes, which leads to the possibility of more in-depth consideration of possible upgrades. Introduction of machine learning methodology into such simulations has also facilitated prediction accuracy as revealed by Kumar N et al. [5] and Rajendra M et al. [6] who used advanced algorithms to identify the correlation between design variables and performance results. As can be seen in the work of Appalasamy K et al., [7] and Kurnierwati I et al., [8], field studies reveal the need to know laboratory results in real-life. By evaluating the local weather and environmental conditions on solar panel performance, these studies address the gap in theory and practice by determining the impact of local climatic and environmental conditions on solar panel performance. Moreover, multi-method, which combines experimental, computational and field data, has been considered to be especially strong in the literature, as demonstrated by the comprehensive analysis of Iskenderov U et al., [9] and Shi Yet al., [10]. These synergized approaches do not only make clear the intricacies of thermal management in silicon-based solar panels but also make it very clear that interdisciplinary approach is an essential way to develop further into this sector. The literature that is available on the subject of the thermal performance enhancement of silicon-based solar panels displays an intersection of theoretical views leading to either a defense or criticism of the existing methodologies. Much attention is given to passive cooling methods and different researchers prove efficacy of reflective coating and improved convectional systems to reduce the thermal accumulation, which can impair the efficiency of photovoltaic panels [1][2]. On the other hand, the presence of active cooling mechanisms, including water- and air-cooling systems is actively examined, and some researchers believe in their effectiveness in obtaining the maximum energy output at high-temperature conditions [3][4]. Also, the research of new materials showcases the opportunities of advanced thermally conductive materials to enhance the process of heat dissipation. As an example, the recent discoveries show that the addition of phase change materials can considerably smooth out the changes in temperature and thus enhance the work of solar panels [5][6]. Also, the literature review highlights the significance of environmental conditions, which affect solar panels performance, including wind speed and ambient temperature in the interaction with thermal characteristics [7][8]. It is also worth noting that the comparison between the theoretical models and the empirical data also enriches the discussion. There are studies that suggest a multi-faceted approach where various enhancement methods are used to bring about holistic changes in thermal management[9] [10]. However, this approach is yet to be widely accepted; instead, other approaches propose that simplification within the system may lead to more feasible solutions [11][12]. In this regard, the literature review implies that there is a complex environment within which advancements must be made between technology and theoretic concepts to promote solar energy optimization.

CONCLUSION

The evidence of the literature on thermal performance improvement strategies of silicon-based solar panels has provided a mine of information that is critical in the development of this paramount area of the solar technology. One of the main findings is that cooling techniques have been successfully used to alleviate thermal degradation- such an aspect is extremely essential since it reduces the efficiency of the photovoltaic systems when the temperature is high. Passive cooling as a strategy that involves utilization of natural cooling airflow and active cooling strategies which include water cooling and hybrid photovoltaic thermal systems have demonstrated significant potentials of enhancing energy output and extending panel life cycles [1][2][3][4]. Moreover, the development of new materials making them thermally conductive or phase change materials is also opening an important prospective of improving heat regulation with new surface treatments [5][6][7]. The general idea of this review is that the thermal management of silicon solar panels needs a complex approach. Since studies have always pointed out the shortcomings of the sole-use of any approach, the literature in general disagrees on any one approach as it is likely to yield the best outcomes [8] [9]. This integrative approach is crucial because it reflects the significance of interdisciplinary partnership between the engineers, material scientists, and specialists who consider sustainability in the search of comprehensive solutions that can not only enhance performance but also be able to align with the vision of sustainability [10][11].The implication of these results goes well beyond optimizing efficiency; they mark a major stride in the quest of realizing the entire potential of solar energy as a sustainable resource in the fight against climate change. As solar energy is being promoted as a crucial element of the global energy transition, the implementation of strategies aimed at enhancing thermal performances will be directly involved in the expansion of the renewable energy usage and economic feasibility. A plant that employs solar panels based on silicon and these innovations can achieve a reduction in operation costs and market competitiveness thereby increasing their reach and usefulness [12] [13] [14][15]. However, there is no literature that is free. To a great extent, the majority of the available studies have been limited to a subset of experimental validations or theoretical models, creating a fractured understanding of the current state of thermal management [16][17] .Even then, most of the existing studies have not been conducted in a comprehensive manner to validate the offering useful techniques as have been reported in these reviews, all of which casts doubt on their applicability across a wide range of climatic and geographical settings [18][19][20].Future studies should, therefore, focus on the conduction of large-scale empirical studies and practical application to It is also evident that there is an exploration gap on the long-term implication of newly developed materials and their sustainability profile once it is incorporated in the solar technologies. The tests of the future ought to also aim at developing a relationship between thermal performance and lifecycle tests that would help create a better picture of what such improvements would entail [21][22]. The two domains offer fertile grounds in terms of scholarships that may be used in shaping future technological growth, and commercial applications. To sum up, the given literature review can not only summarize the existing knowledge of the ways to improve the thermal performance of silicon-based solar panels but also indicates the important research directions that could further increase the efficiency, adaptability, and sustainability of solar energy systems in the nearest

Table 1. Summary table of prior research

Author	Year	Main Focus	Findings
M. J. Talukder, et al. [1]	2025	Evaluating advancements in high-efficiency solar photovoltaic materials, especially perovskite solar cells and tandem technologies.	PSCs have achieved efficiencies over 25% in single-junction and 29% in tandem configurations, with significant stability challenges remaining.
G. Badran et al. [2]	2025	Examining recycling challenges and opportunities for photovoltaic solar cells to enhance sustainability.	Identifies the need for improved recycling infrastructure and highlights the potential of integrating design-for-recyclability principles to enhance material recovery.
I. Subedi, et al.[3]	2020	Using optical probes to evaluate photovoltaic device performance and diagnose losses.	Demonstrated effective optical modeling for various PV technologies, leading to accurate predictions of device efficiencies.
K. Choubani et al.[4]	2025	Evaluating enhancements in solar still desalination to	Proposed methods resulted in significant increases in water output, indicating effective techniques for thermal

		improve water production.	management.
N. Kumar [5].	2025	Reviewing methods to optimize heat transfer performance in solar collector tubes.	Identified strategies such as advanced materials and nanotechnology as key to improving thermal efficiency.
M. Rajendra, et al.[6]	2025	Exploring advancements in solar thermal systems and the integration of hybrid architectures.	Advanced materials and nanofluids significantly improved thermal efficiency and energy retention in solar thermal technologies.
K. Appalasamy, et al.[7]	2025	Reviewing cooling techniques to enhance efficiency of photovoltaic systems.	Identified innovative cooling strategies that effectively reduced thermal buildup and increased performance.
I. Kurniawati et al.[8]	2024	Reviewing technologies aimed at improving heat management in photovoltaic-thermal systems.	Identified various innovative approaches to enhance energy transfer and reduce inefficiencies in PV-T systems.
U. Iskenderov et al.[9]	2024	Investigating optimal heating structure configurations for improved energy efficiency in	Highlighting effective technologies that significantly reduce energy consumption while

		buildings.	enhancing thermal comfort.
Yuxin Shi [10]	2024	Reviewing molten salt energy storage technology in solar thermal applications.	Identified improvements in thermal properties and reductions in costs, while emphasizing ongoing challenges.
F. Ullah et al. [11]	2024	Investigating enhancements in heat transfer for thermal energy storage systems.	Demonstrated significant improvements in efficiency through innovative applications of graphite sheets.
F. Uba et al. [12]	2021	Evaluating thermal performance of solar collectors in humid weather.	Identified design improvements leading to enhanced thermal efficiency and performance under challenging weather conditions.
D. Sinaga et al.[13]	2025	Analyzing improvements in photovoltaic performance via a dual-axis solar tracker system.	The combined approach significantly increased energy output and efficiency.
C. Lakshmi et al. [14]	2024	Quantifying impacts of factors affecting solar panel efficiency in tropical climates.	Identified enhancement techniques that significantly boosted solar panel efficiency.

L. Koshy et al. [15]	2024	Developing an efficient fault detection system using thermal imaging for solar panels.	Achieved high accuracy in detecting anomalies, enhancing the operational reliability of solar systems.
M. Vetrivel et al.[16]	2024	Evaluating the integration of nanostructured ZnO layers with silicon solar cells.	Significantly improved performance metrics of silicon cells through reduced recombination losses.
M. Z. Ab Hamid, et al. [17]	2024	Developing a method for hotspot detection in solar panels utilizing YOLOv9.	Achieved improved accuracy and localization for effective maintenance.
A. Roy et al. [18]	2023	Optimizing multi-junction solar cells for increased performance.	Demonstrated significant improvements in solar cell efficiency through optimized doping profiles.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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Functionally Graded Materials for Biomedical Applications: A Review

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ABSTRACT

FUNCTIONALLY GRADED MATERIALS HAVE EMERGED AS A NEW HORIZON IN THE FIELD OF BIOMATERIAL RESEARCH FOR THEIR CAPABILITY TO OFFER CUSTOMIZED STRUCTURAL AS WELL AS BIOLOGICAL PROPERTIES BY THE CONTINUOUS VARIATION IN THEIR COMPOSITION AND MICROSTRUCTURE. THE LATEST DEVELOPMENTS IN THE DESIGNING, PROCESSING, ANALYSIS, AND APPLICATION OF FGMS FOR A RANGE OF BIOAPPLICATIONS HAVE BEEN REVIEWED CRITICALLY. A RANGE OF TOPICS CONCERNING THE OPTIMIZATION OF FUNCTIONALITY FOR FGMS HAS BEEN REVIEWED IN THE CONTEXT OF THE GROWING NEED FOR THE ADOPTION OF INTERDISCIPLINARY RESEARCH STRATEGIES THAT EFFECTIVELY COMBINE THE EFFICIENCY OF SIMULATION STRATEGIES ALONG WITH THE STRENGTH OF EXPERIMENTALLY DRIVEN RESEARCH. APART FROM HIGHLIGHTING THE NEED TO TACKLE CHALLENGES IN THE LONG-TERM BIOCORROSIVITY OF FGMS FOR REACHING THE REGULATORY NECESSITIES IN THEIR APPLICATION IN THE HEALTHCARE INDUSTRY, THE RANGE OF APPLICATIONS THAT HAVE BEEN REVIEWED IN THE ARTICLE INCLUDES THE ANALYSIS OF FGMS IN THE FORM OF A SCAFFOLD FOR A RANGE OF BIOAPPLICATIONS, DRUG DELIVERY CARRIERS, AND MORE.

KEYWORDS: FUNCTIONALLY GRADED MATERIALS (FGMS), BIOMEDICAL APPLICATIONS, ADDITIVE MANUFACTURING, BIOCOMPATIBILITY, OSSEOINTEGRATION, SMART BIOMATERIALS

1. INTRODUCTION

The needs of modern medicine have become complex to the point where new approaches have to be developed. This includes material sciences together with bioceramics. The challenges in research for the new generation of bioceramics include challenges in the field of material sciences. The challenges in research for the new generation of bioceramics include challenges in the application of material sciences to medicine. Tissue engineering, implanted devices, and drug delivery systems have become challenges for the research community in material sciences. These challenges have resulted in the need for the development of functional graded materials (FGMs). These have the benefit of optimized performance via properties dissimilar in space. The uniqueness of FGMs resides in the gradual change of the material structure and composition, thus improving functionality and biocompatibility [1]. They have strengths, elasticity, biodegradability, and other property-tailoring characteristics, which match tissue requirements, and they are useful in orthopedic implants, cardiovascular devices, etc. [2]. Recent studies of FGM have demonstrated that they are capable of stress reduction at material interfaces such that the life and performance of implants could be extended [3]. Much of the literature is dedicated to the design and manufacturing of FGM, biocompatibility and biomechanical functioning [4]. It has been found out that polymers, ceramics, and metals combine in graded proportions to remarkably enhance their mechanical and biological properties [5]. With current advancements in the additive manufacturing, complex shapes and gradients can now be formed, forming custom solutions that recapitulate the hierarchies of natural tissues [6]. Nevertheless, even in the situation of advancement, we should still learn more about the behavior of FGMs in the long-term physiological conditions since most studies are related to short-term effects [7]. There are also difficulties with translating the laboratory findings into clinical practice, including regulatory approval and in vivo testing [8]. Biomechanical and surface characteristics of FGMs are also a theme and studies have demonstrated the influence of microstructure on biological responses [9]. Some of the applications studied include surface treatments and functionalization to increase the bioactivity of FGM [10]. But a complete knowledge is required, not only on the mechanical properties but also on the long-term biological interactions under various environments [11]. This review focuses on consolidating the existing information on the topic of functionally graded materials in biomedicine and identifying the prospects of research in the future. Analyzing the current literature, we point out the major innovations and current issues of the application of FGMs to practical medical environments [12]. Another aim of this review is to bridge the gap between materials science and clinical uses with the requirement of the integration of materials with the biology system and regeneration facilitation [13]. This initiative could offer perspective into the forthcoming research, which might result in research breakthroughs in the design and use breakthroughs [14]. In the end, it is becoming more and more evident that FGM utilization optimization is likely to bring about a revolution in the field of personalized effective medical equipment and improved patient care [15].

2. REVIEW OF LITERATURE

The landscapes of functionally graded materials (FGMs) in the medical sector have been of high interest in the last years. In reality, the pioneering studies have focused the attention on the structural aspect.

The gradients of the FGMs have been shown to have a positive effect on the points of stress for the implants [1], [2]. These studies have radically preconditioned the verification of the possibility to utilize the FGMs to improve the bonding between the implants and the body tissues [3]. As the events continued to develop, more attention was given to the type of material used. Indeed, people have become more aware of the functionality of the research material concerning the body. Recently, even more stress has been made on the importance of changing the values of the gradients in order to repeat the composition of our body for easier healinging [4], [5]. To give indicative examples of the point in reality reached, some researchers have succeeded in utilizing the additive manufacturing for the production of the FGMs in complex shapes more predisposed to deal with the corresponding biomedical needs [6], [7]. Apart from the above application of the FGMs, there also exist different researches in the drug delivery systems. The gradients for the unloading of the medication offer new horizons in therapy filled with a great deal of passion [8], [9]. All of the above indicate a diversification that point to a greater trend of personalized biomedicine. There exists a need to apply the knowledge of the different biomaterials tailored to the different conditions of the corresponding patients in a medical context. More recently, there have been applications of the modeling. The combination of the modeling studies with the experimentations has resulted in the verification of the possibility to simulate the corresponding design of the FGMs. Indeed, all of the above have resulted in the capability to further fine-tune the corresponding mechanical and biological ones by simulation studies [10], [11]. All of the above studies taken together show a tendency to some improvements. Indeed, the basic concepts have developed to a higher degree of comprehension of all the different possibilities of the applications of the FGMs. The study of the functionally graded materials (FGMs) in the biomedical sphere has also introduced new themes, stating their significance and possibilities. The mechanical qualities required to make biomedical implants, which are biomechanically modified to fit the tissue requirements are one of the fundamental themes. It was found that FGMs are superior to normal materials in their mechanical characteristics and enhance the performance and service life of implants [1], [2]. Furthermore, gradients of materials support the process of osseointegration as it has been found that osteoblasts adhere and proliferate on graded surfaces more successfully [3], [4]. The other important theme is that of biocompatibility, as FGMs appear promising in the context of reducing inflammation and promoting healing. The low cytotoxicity has been associated with better coating techniques and gradient formulas to enhance the body reaction to implants [5], [6]. Also, FGMs have a high level of drug delivery, in which their graded structures have the ability to manage the release profiles and enhance therapeutic outcomes [7], [8]. Improvements in technology of the production of these materials are also included, and an additive manufacturing technique is needed when defining complex FGM structures [9], [10]. This technological advancement assists the application of FGMs by FGMs in sub-medical tasks like orthopedic and dental fixtures and this provides a range of novel biomedical solutions [11]. As observed in the study, FGMs enhance functionality and are more compatible with biological systems by incorporating different material properties, and this is a first step towards changing the field of biomedical engineering. The application of functional graded material (FGMs) in biomedical practice has been considered in different aspects which affected the manufacturing and application of such advanced materials. In order to test the applicability of functionally graded materials (FGMs) to biomedical applications, there is a recent tendency to integrate mechanical and biological testing. The computational modeling is crucial in the prediction of the FGM behavior in physiological conditions as well as the designing of the best structures. The possible applications of FGMs to load-bearing medical implants were confirmed by the fact that Panchal and Ponappa [5] have shown that a finite element analysis is useful to simulate the stress distribution in composite systems. These predictions should be supported by experimental research to prove themselves and test their biological performance in reality. According to Bandyopadhyay et al., in vitro and in vivo testing plays a vital role in ascertaining mechanical reliability and biocompatibility, which are error-free to clinical success [2]. An integrated approach that incorporates modelling and experimental validation has been able to find a potent framework of the development of FGM. The interdisciplinary approaches made possible by the works of Teo et al. [3] and Zhang et al. [4], who promoted the need for the design process to be based on the iterative approach of design, bridging the expectations of theoretical concepts and the reality of empirical evidence. These designs also recognize the importance of interdisciplinary collaboration for the fields of material science, mechanical engineering, and biomedicine. Additionally, our current understanding of the micro-structural influence on the performance of FGMs has been significantly heightened thanks to the latest generation of characterization tools including the micro-computed tomographic scanner and the scanning electron microscope [1]. Taken together, the development of these allows the utilization of experimentally driven, computationally supported, or theoretically driven techniques to stretch the boundaries of FGM applications in the field of biomedical engineering. Interestingly enough, there also seems to be a growing community acceptance of the need for compositional gradients to match the range of values of the different natural biological tissues to simplify the process of incorporating FGM into the world of medicine. This improves their application in the form of transplants for both implants and prosthetics [1], [2]. All of this information can be applied to supply a strong theoretical framework in which the tailoring of material properties be made possible by the design of gradients. More importantly, the controversy relating to bioactivity suggests the presence of contrasting opinions. There also exist contributors who show that the development of gradients would greatly improve the application and efficacy of the transplanted items by recreating natural constructions of body tissues [3], [4]. There also exist warnings about the difficulties of trying to implement a semblance of strength in the gradients presenting the potentials for long-term risks identified [5]. These contradictions present the need for further research. Interestingly enough, modeling techniques have expanded to account for the presence of these conflicts to serve the purpose of the prediction of functionality under body conditions. Finite researches have already shown how the designs of the gradients have the capability to redefine the stress gradients that have a direct effect on the entire “life span” of the items in the application in the field of medicine [6], [7]. Even the combination of the hard facts of reality applied to the modeling technique also contributes even more to the growing body of information since there exist attempts to correlate the theoretical ideas to the empirical findings of the biological events [8], [9]. All in all, the application for the analysis of the FGM in the world of medicine demonstrates the evidence of the continuous change between the theoretical concepts and the applications derived. Even though the FGMs show great promise, the community has to deal with the theoretical inconsistencies present in the technology. Additionally, the techniques to implement the developments into a promising health efficacy need to be improved.

Functionally graded materials (FGMs) have shown the potential to improve patient care by providing tailored and functional applications for the application. A great deal of attention in the research has been devoted to their properties of being mechanically compatible in the body. They seem to have a good compliance to the biomechanics of the body tissues. This may lead to the achievement of greater and more long-lasting functionality of the implant [1], [2]. FGMs have been considered a revolutionary technology in the medical devices industry owing to their mechanical compatibility function of assisting in the osseointegration process [3], [4]. There comes the innovation in the processing of the material, particularly the application of the Additive Manufacturing. Scientists have been successful in designing complex designs having normalized material variation. These designs have similarities to the complex designs of the natural material. These designs can be applied to all types of orthopedic implants to the drug delivery systems [5], [6]. This correlates to the changing trend in the application of personalized medicine. Now the biomaterials have become more personalized to suit the needs of the patient [7]. The net result of all these factors is not merely research. Rather, there has been a true innovation in the field of material science and biomedics. Some of the prominent advantages of the FGM material have been their improved biologically active characteristics. They have the prospect of providing improved clinics healing success rates due to their improved biologically active characteristics [8]. Besides that, FGMs have potential in terms of drug delivery, which opens the possibilities of customized treatments that can enhance the care of patients [9]. Nevertheless, despite all the advancements it has some significant things that we have to take into account. Indicatively, there is no full understanding of the behavior of the FGMs in the body in the long-term. The duration of time biological interactions can influence their effectiveness is not investigated in many studies [10]. Besides, despite the promising in vitro results, the use of these materials in the real clinical setting is a difficult task due to the regulations. In vivo research is required to verify their safety and efficacy [11]. These issues should be discussed in future researches. Research would be able to investigate the treatment of FGMs in the body in the long term in various clinical conditions giving a better picture of the way they decompose and how the body responds to them [12]. Moreover, cross disciplinary efforts through computerization and experimentation may enable us to refine FGM designs to be even better applied in biology [13]. It is also a nice thought to see how the surfaces of these materials can be altered to increase bioactivity, which would come in handy when it comes to issues of cytotoxicity and bio-responsiveness [14]. In conclusion, the FGMs have many applications in the promotion of the utilization of biomed. The combination of the innovations derived from material science in the healthcare needs will see the manner in which patients receive medical attention change for the better. But in order to maximize them we still need to study and confirm these sources with long-term research and interdisciplinary studies [15]. These developments may be applied in the field of biomedical engineering to bring about a new dawn of individual and efficient solutions to different healthcare requirements [16]. Biomedical engineering is evolving so fast owing to the amalgamation of novel functional materials in addition to hybrid fabrication techniques. Cartilage repair is a promising field of 3D bioprinting. Spatial regulation of material gradients was reported to have a strong positive effect on tissue repair and mechanical compliance with native tissues, which have definite analogies to functional principles of the design of functionally graded scaffolds [17]. At the same time, technologies of additive manufacturing have enabled the production of complex material transitions and geometries. To be clinically viable, FGMs require that these technologies can permit a deposition of biocompatible materials that contain specific properties [18]. Photodynamic treatment is a light-activated treatment that opens up new opportunities of localised treatment delivery, and this once again demonstrates the way in which bioresponsive materials can be developed to respond dynamically to biological systems [19]. The bioactive systems form significant aspects of regenerative medicine. As an example, platelet-rich fibrin (PRF) has been studied when used in graded constructs in order to enhance bone regeneration [20]. Scaffolds made with programmable distributions of pore size can also be used to recapitulate the mechanical performance and transport behavior of native tissues and are produced using advanced methods based on laser tools [21]. New hydrogel systems facilitate this development. High biocompatibility and tunable mechanical characteristics of smart hydrogel have enabled the integration of responsive layers into FGMs in order to enhance their adaptability and biological functionality in vivo [22]. Such advances indicate that there is an increased convergence between biological integration, functional responsiveness, and material architecture. This direction complies with the bigger objective of patient-centric and versatile therapeutic platforms, which confirms the role of FGMs in the biomedical devices of the future.

Novel cross-disciplinary directions now highlight the importance of integrating technological progress with clinical relevance to make the best of the biomedical and clinical possibilities of functionally graded materials (FGMs). The two key impediments to the implementation of FGMs in the medical practice are complex regulations and lack of knowledge about the long-term biological interactions. Considering this, Regev et al. [23] emphasized the value of extensive biological mapping through the Human Cell Atlas, the latter of which, in turn, can be of much help when it comes to designing biomaterials to fit specific cell conditions. Blocher and Perry [25] also discussed the potential of coacervate systems as controlled release and bioactive encapsulation methods which could be useful in FGM-based therapies, and DiCiccio et al. [24] examined caffeine-catalyzed hydrogel and suggested new soft materials to use in dynamic biology. FGMs are under continuous development due to the sophisticated methods of fabrication, e.g., 3D printing. Just like the motivation of individualized micro-architected FGMs, Au et al. [26] looked into the impact of 3D-printed microfluidics in the biomedical systems. Koh et al. developed real-time biochemical wearable microfluidic devices [27]; these technologies can complement smart FGMs to carry out drug delivery or diagnostic functions. The 3D bioprinting of cartilages was also demonstrated by

Perera et al. [28], who emphasized the ability to control mechanical gradient to be applied in the printed implants to replicate the behavior of native tissues. Also, nanostructured materials can enhance the properties of FGMs. Reina et al. [29] in their discussion of the biomedical potential of graphene indicated that although it is very strong and has high biocompatibility, toxicity and clinical approval are still a problem. Among ten grand challenges in science robotics identified by Yang et al. [30], the biointegration and functional optimization of FGMs in the context of soft robotics or prosthetics are also mentioned. In the field of bone tissue engineering, Zhou et al. [31] selectively laser melted to produce functionally graded scaffolds with programmable pore structure that has controlled degradation and strength under load bearing conditions. According to the study done by Iandolo et al. [32] on organic electronic scaffolds to osteogenesis, electrical functionality can also be added to FGM systems. Chia and Wu [33] reported the progress made on 3D-printed biomaterials enhancing cellular guidance and integration, which is a key goal in implantable FGMs. Hydrogels and surface chemistry are still necessary to be biocompatible. They both can be altered as layers or surface treatments in graded implants. The hyaluronic acid hydrogels have been discussed by Burdick and Prestwich [34], and platelet-rich fibrin (PRF) has been discussed in the context of bone regeneration by Farmani et al. [35]. To directly endorse the mechanical-bioactive binary that is needed in FGM surfaces, Chen and Jia [36] explored multilayer hydroxyapatite coating through laser deposition. More general conceptual issues are also discussed. Yap et al. [37] reviewed selective laser melting in a range of industries and revealed how the post-processing variables that influence quality of the surface and residual stresses have to be considered to optimize FGM with design as another factor to consider. Oberdorster et al. [38] in their significant contribution to the field of nanotoxicology have advised scientists that despite the promise of the use of FGMs with nanoparticles or new chemistries, a comprehensive toxicity evaluation should be performed prior to clinical translation. Together, these sources [2338] contribute to the evolution of FGMs outside the ordinary biomedical models as they contribute to the complex nature of the practice. Along with presenting the principles of design and providing technologies, they attract attention to the problem of translational barriers that are to be crossed before FGMs can be integrated into the next-generation medical equipment. Table 1 provides a summary of the literature review.

Table 1. Literature Review Summary

Author	**Main Focus**	**Findings**
Alkunte et al. (2024)	Examine advancements and challenges in additively manufactured Functionally Graded Materials (FGMs) and their applications.	FGMs hold significant potential due to their adaptable properties in various applications. The review highlights challenges in production and performance and forecasts future trends.
Bandyopadhyay et al,. (2023	Review manufacturing processes, properties, and challenges of porous metal implants in biomedical applications.	Porous biocompatible metals offer tailorable strength and fatigue resistance, making them suitable alternatives for orthopedic and dental implants.

Teo et al,. (2022)	Analyze nanocellulose as a Pickering emulsifier for various non-toxic applications.	Nanocellulose provides a sustainable alternative for stabilizing emulsions, with potential applications in the food, cosmetic, and pharmaceutical industries.
Zhang et al. (2022)	Explore bioinspired designs for soft-hard tissue interfaces and their application in engineered materials.	Mimicking natural soft-hard interfaces can significantly enhance the performance of biomedical devices.
Panchal and Ponappa (2022)	Review computational methods and production techniques related to functionally graded materials (FGMs) in biomedical uses.	Existing advancements in computational modeling improve biomedical outcomes, yet gaps remain for practical integration.
Li et al. (2020)	Review multi-scale design concepts in additive manufacturing of FGMs and FGSs.	Proposed strategies for multi-scale designs significantly enhance the functional performance of FGMs and FGSs across various industries.
Petit et al,. (2018)	Explore graded ceramics for their potential in biomedical applications, focusing on their unique properties.	FG ceramics offer significant advantages over traditional materials, enhancing the performance of biomedical applications.
Mahmoud and Elbestawi (2017)	Overview of additive manufacturing applications of FGMs and lattice structures in orthopedic	Highlight successful case studies and identify critical challenges that need to be addressed for better

	implants.	performance.
Gillies et al. (2015)	Examine the use of radiomics in transforming medical images into actionable data.	Radiomics enhances diagnostic accuracy but requires standardized processes for broader clinical integration.
Mehrali et al., (2013)	Review advancements in FGMs for dental implants, focusing on properties and manufacturing techniques.	FGMs show superior properties for dental applications, improving biocompatibility and osseointegration.
Bulcha et al., (2021)	Review the current landscape of viral vector platforms in gene therapy.	Despite successes, significant challenges remain that limit the full potential of viral vector approaches.
Seddiqi et al., (2021)	Survey the structural properties of cellulose and its potential applications in biomedicine.	Cellulose derivatives hold promise for various biomedical applications, though underutilized relative to industrial uses.
Homaeigohar and Boccaccíní (2020)	Review advances in antibacterial nanofibers for wound dressings.	Biohybrid nanofibrous dressings show promise due to biocompatibility, biodegradability, and enhanced healing properties.
Yang et al., (2018)	Identify ten grand challenges in the field of Science Robotics.	Tackling these challenges could lead to significant advancements in technology and social applications.

Regev et al., (2017)	Outline the Human Cell Atlas Project aiming to identify all human cell types.	The project could significantly enhance understanding of human biology and disease.
Reina et al., (2017)	Evaluate the potential contributions of graphene in biomedical applications.	Graphene shows significant potential but faces challenges regarding biocompatibility and regulatory approval.
Koh et al., (2016)	Develop a skin-mounted microfluidic device for sweat analysis.	The device enables non-invasive health monitoring and effectively measures biochemical markers in sweat.
Blocher and Perry, (2016)	Explore coacervate materials for biomedical applications.	Complex coacervates show promise in encapsulation and as scaffolds in tissue engineering.
Au et al., (2016)	Examine the impact of 3D printing on microfluidics.	3D printing offers significant advantages over traditional methods, improving design flexibility.
Perera et al., (2021)	Explore advancements in 3D bioprinted implants for cartilage repair.	3D bioprinting shows promise in creating functional constructs with modulated mechanical properties for cartilage tissues.
Wong and Hernandez, (2012)	Review current advancements and challenges in additive manufacturing.	Additive manufacturing is revolutionizing industries but faces challenges in material usage and accuracy.
Agostinis et al.,	Update on the efficacy and	PDT shows significant

(2011)	applications of photodynamic therapy (PDT) in cancer treatment.	potential, especially in early-stage tumors, with minimal side effects and good outcomes.

3. Conclusion

Functionally graded biomaterials represent a new class of biomaterials that can solve the complex problems of modern biomedical applications. Due to their unique ability to exhibit gradual variations in composition and structure, their mechanical properties, biological response, and material behavior can be tailored for diverse spatial regions in specific applications such as implants, dental prostheses, and drug delivery systems. In the foregoing review, prominent trends in the design, processing, and evaluation of FGMs for different applications in the field of biomedicine have been pointed out. In the context of research studies, the capability of FGMs to not only offer improved biocompatibility based on bioactivity but also promote osseointegration and inhibit a biological rejection has been emphasized.

Despite the above advancements, a number of challenges continue to exist. Biocompatibility for long periods of time, degradation rates, and in vivo stability of FGMs remain to be investigated. These challenges include some of the greatest concerns for general adoption. Implementation of intelligent capabilities in the form of bioactive substances or responsiveness to biologically significant stimuli in graded material systems also presents another direction to move ahead. Unlocking the complete potential of FGMs will therefore involve a multidisciplinary approach in one interface of material sciences, biologists, mechanicians, and healthcare research. The application of FGMs would therefore be more significant in the coming era of customized high-performance biodevices since they would have the capability to span both theoretical modeling of experiments.

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Hydration Retardation in Cement-Based Materials: Chemical Admixtures, Natural Retarders, and Emerging Alternatives – A Review

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Abstract

Hydration Retardation: A Review of Literature relating to Cement-based Materials. Actually, hydration retardation is one of the major methods used to handle fresh as well as hardened properties of cement-based materials. This review would provide a systematic update of literature available regarding methods for hydration retardation with special focus being given to the main types of methods for hydration retardation. This would also include conventional methods of using chemicals such as lignosulfonate compounds, sugar derivatives, as well as organic acids. There is a growing interest in natural and bio-based retarders based on agricultural by-products and plant extracts, which may have lower environmental impact but do not sacrifice a performance that is satisfactory. Moreover, the new alternatives such as bio-based polymers, nanomaterials, and high-level synthetic compounds are also discussed in terms of their effects on the kinetics of hydration, microstructural formation, and long-term stability. The review is also conducted on experimental and analytical methods to assess hydration retardation like calorimetry, spectroscopic methods, and microstructural analysis. The gaps in the existing knowledge are found especially with respect to comparative performance, synergistic effects, standardization, and applicability to fields-of-use. In general, the purpose of the review is to offer a combined insight to researchers and practitioners with regard to the hydration retardation strategies and to aid the creation of more sustainable and reliable cement-based materials.

Keywords: Hydration retardation, Cement-based materials, Chemical admixtures, Natural retarders, Bio-based materials, Setting time.

1. Introduction

The performance level of cement based materials is determined by the complex interaction among chemical constituents of the material, but hydration is a significant process that affects the mechanical properties, the durability and the overall long life of the material. The knowledge of how to manipulate and retard such a hydration process has become a subject of much interest both in academic and in industrial circles particularly as the construction industry endeavors to find new ways of working in order to increase efficiency and sustainability. Since time immemorial, chemical admixtures have been used to lengthen the workability of concrete mixtures in the certain conditions and enhance the performance of concrete mixtures in a diverse range of environmental conditions [1]. The difficulty of rapid hydration during hot climate or long transportation durations has however stimulated study on alternative methods of retardation. The natural retarders are also an alternative to the use of aluminum oxide but they are based on the agricultural or bio-based materials and this is a good prospect of sustainable construction practices with both environmental and economic advantages [2] [3]. Newer synthetic compounds with lower environmental effects and greater functionalities are just emerging and are starting to change the perception of the hydration behavior in cementitious systems [4]. The importance of the research is hard to overestimate, as the environmental factor of climate and the lack of resources promote development of the construction processes and cause the tendency to resort to more environmentally friendly materials and technologies [5]. Themes of hydration retardation have a wide range of factors as described in the existing literature, including the physicochemical mechanisms involved, the performance effects of different retarders and long-term durability implications [9] [10]. Methodologies used to measure hydration retardation have also evolved with both empirical approach and sophisticated modeling used to investigate the complexity of these relationships [9] [10]. Moreover, systemic reviews have determined the key performance indicators required to determine the effectiveness of retarders, thus, the study has helped in understanding their use more comprehensively [11]. However, there are critical gaps in the literature that still exist. As an example, there is no detailed research on the performance of conventional and emerging retarders, especially in different environmental settings [12]. Synergistic interactions among various retarders and their long-term effects on the mechanical properties are still under widespread research since they may have a profound implication on the practical applications [13][14]. Furthermore, although natural retarders have a bright future, the research on this topic needs to be conducted again to standardize their application and protocols of mixing and application [15], [16]. The scalability of these options is yet another area that should be addressed since most of the promising solutions are only available in laboratories without adequate real-life applications [17], [18]. This literature review will attempt to fill these gaps with the detailed examination of the current and new strategies of hydration retardation in cement-based materials. Through comparison of existing methodologies, synthesis of results of various studies as well as possible future research avenues, the review will add to the comprehensive understanding of the hydration dynamics. Moreover, it will determine the place of chemical admixtures, natural retarders, and new substitutes in the greater context of sustainable construction, therefore, preparing the way to future research and inventions in the sphere [19], [20], [21], [22], [23], [24], [25]. By this means, it shall seek to enlighten not only the practitioner but also the researchers about effective methods of retardation but shall also promote a collaborative approach regarding how a dilemma in hydration processes may be treated. Finally, this review shall broaden our current theoretical and practical awareness concerning modern developments in the field of cement science based upon emphasis brought about regarding this matter [26], [27], [28], [29], [30].

2. Review of literature

The hydration retardation effect of cement-based material, which has been discovered, proves conceptualization and application of chemical admixtures and natural and new substitutes for admixtures to have developed with time. Original research work in this field was overshadowed by the use of traditional chemical admixtures that were critical in controlling setting time of cement. These studies indicated that lignosulfonate derivatives and sugar compounds such as Calcium Lignosulfonate would be utilized as a hydration agent involved in construction activities as a function of where latency properties were applicable [1][2]. As literature evolved with time, environmental issues and sustainability involved with using such types of chemical compounds were put in the limelight. This focus towards where natural retarders were agricultural by-product derivatives marked a beginning with new research studies being effective with less environmental implications than were being witnessed when used as a means for effective synthetic counterparts [3][4][5]. Literature of previous years signifies a rising inclination towards researchers finding novel approaches such as bio-based types and methods using nanotechnology. This has culminated in effective studies being generated with a focus on learning about retarding effect mechanisms in a more profound manner while learning about history of methods of retarding synthesized along with developments within the industry with changing standards involved with this particular field of operation associated with regulation standards involved within [9][10].This interwoven massives of researches indicate a more radical course of action through a shift towards more sustainable-creative approach to issues, rather than the traditional and synthetic approach to the job, which will result in improved performance and environmental friendliness of cement-like materials in the construction of buildings [11][12]. As such, the available literature brings to light an urgent point of intersection of technology, sustainability, and practice of the hydration retardation study. The research of hydration inhibition in cementitious materials reveals that the phenomenon is quite complex and includes the mixture of various chemical admixtures, natural factors of retardation. It is notable that the chemical admixtures such as superplasticizers and retarders are significant in the control of the setting times, the workability as well as the long-term performance of the concrete. It has been found that some of these admixtures can significantly delay the hydration processes and allow the concrete mixtures to be used under harsh environments to be utilized over an extended duration of time [1][2]. This is induced in the literature in which after numerous studies, it is demonstrated that various chemical formulations can give the desired effects of hydration retardation [3][4]. Other than the use of synthetic solutions, natural retarders also provoke the interests of sustainable practices in cement chemistry. The literature has made the efficacy of biobased natural retarders, such as sugar derivatives and hydrocolloids, in influencing the hydration rates without influencing the structural integrity [5] [6]. The growing popularity of such organic materials is a sign to change to more environmentally friendly concrete production methods [7][8] New variations in particular those of nanotechnology are indicated as potentially proffering alternative ways of modifying the properties of cement based materials in terms of hydration. It is suggested that nanomaterials can be effective enhancers of the microstructural properties and are useful as retarders [9][10]. This hybridization between the old wisdom and the new development is a dynamic situation and such addition of the special additives does not just postpone the hydration process, but also the sustainability agenda in the building industry [11][12]. In general, most literature points towards integration of several methods of retardation leading to a requirement for comprehension regarding implications in fresh and hardened concretes more effectively. The analysis connected with hydration retardation in cement-based materials points towards several strategies employed through methods followed being of utmost importance regarding achievement of accomplishment connected with the chemical admixture and natural retarder along with several other alternatives. For example, experiments along with computational analysis help regarding data enabling effective information regarding methods being followed in accordance with chemicals affecting hydration process. This leads to capability regarding several admixture processes such as lignosulfonate along with sugar evidencing diverse effects regarding workability along with other effects regarding retardation [1], [2], [3]. Additionally, utilizing natural retarders along with experiments regarding material being used would comprise agricultural by-product evidencing additional sustainable alternatives regarding modification regarding hydration properties. This indicates that these natural alternatives would attain additional enhanced effects with less effects regarding natural earth, indicating a two-fold advantage [4], [5]. New methods regarding experiments particularly evidencing application regarding extremely analytical techniques such as nuclear magnetic resonance along with differential thermal analysis would provide additional information regarding several micro structures evidencing changes regarding hydration [6], [7]. The techniques are capable of giving the chemical interactions in the various temperature and mixture conditions a fine control needed in the investigation of how formulation variants could lead to various hydration behaviours. In addition, meta-analytical techniques involving the synthesis of the data of multiple studies have discovered the shared patterns in the implications of retardation by different forms of admixtures in linking the importance of setting in the interpretation of the results [8], [9]. In this way, the scientific explanations of the hydration retardation can be fortified by these different methodological viewpoints, which in the end can lead to the future research to be more efficient and sustainable towards cement-based materials. There is lots of debate on the performance and processes of chemical admixtures and natural retarders in alleviating hydration in cement-based materials. The different researchers arrive at the same conclusion that the hydration kinetics of chemical admixtures like lignosulfonates and other polysaccharides has a significant effect in creating complexes with calcium ions, which eventually increases the setting times [1][2]. Recent discoveries have also contributed to this point of view by showing that in addition to delaying hydration, these interactions can also be used to improve the workability of concrete mixtures, which is a two-fold advantage to construction applications [3][4]. Additionally, natural retarding agents produced using plant extracts are also being considered as studies have shown that such agents also form a more viable and effective alternative without a compromise in performance. Additionally, certain fruit and seed extracts have shown a better retarding agent effect as illustrated in [5][6]. This notion has lately stressed a transformation towards approaches that are environmentally friendly in light of the sustainability culture being practiced in construction environments [7]. On the other side of the argument exist counterarguments that exist in accordance with differences in levels of efficiency of such retarding agents depending on composition levels and levels of compositions. Certain studies have made a claim about the potential use of natural ingredients culminating in sufficient levels of retarding effect possibilities while others culminate in levels that would potentially lead to uncertainty regarding levels of effects contributed by varying environmental factors [8],[9]. This needs potential levels of uncertainties with regard to its reliance because such researchers claim that this warrants further study to better grasp more regarding levels about levels concerning chemistry involved with this standing right in the center stage of emphasis [10]. Collation of all such theoretical points of view leads towards a total insight regarding such a current scenario existing in such a hydration retarding environment in a manner describing a convergence towards a convergence of such conventional approaches with newer approaches with emphasis towards a great need towards thorough evaluations to ensure a level of uniformity with regard to such resulting levels in diverse approaches.

3. Conclusion

The discussion on hydration retardation of cement-like products can be considered as an in-depth analysis of the shifting future of chemical admixtures, natural one and the new options. Some of the important results include the inseparability between the hydration levels and the cementitious system performance, thus the significance of proper retardation measures applied in optimizing the workability, durability and performance of cementitious systems, at different environmental conditions. $CaSO_4$ lignosulfonates and other sugars amongst other things have long been known to have a pronounced effect of increasing the duration of hydration, which is important in construction works during hot weather, or in construction work that involves logistical delay [1][2]. At the same time, newer literature has moved to focusing on natural retarders based on agricultural by-products that, in addition to presenting comparable efficacy, also have the advantage of providing sustainability benefits due to the lack of reliance on synthetic equivalents [3][4][5]. However, apart from this focus, a new trend has begun to emerge concerning alternatives such as bio-based retarders and nanomaterials. The new approaches encompass novel mechanisms that may be used for further improvement in hydration and performance in the environment [6][7]. As indicated in this literature review, a dynamic debate has evolved among researchers regarding synergies associated with these types of retarders. This literature review indicates that a clear perception regarding how to maximize hydration associated with different regions of application has been put forward [8],[9]. A sum of available knowledge associated with this literature pertains to a possible shift towards a more integrated approach associated with a focus toward sustainable methods without reducing practical performance capability associated with construction material requirements for a high level of performance. However, one must discuss existing limitations associated with this literature. A comparison between conventional methods and newly emerging approaches for retardation remains associated with a prominent level of no comparison among environmental conditions [12][13]. This indicates a prominent level of critical deficit pertaining to this literature. This deficit may be effectively supplemented in future studies, especially those investigating long-term viability associated with synergistic approaches [14]. Moreover, though the potential of natural retarders seems to be promising, research has not yet determined standardized procedures of their application hindering their wider implementation in the industry [15], [16]. The way forward in future studies should be bridging these gaps through comparative analysis and standardisation of methods to prove the effectiveness of natural and emerging alternatives under different situations. Moreover, more attention should be paid to the scalability and applicability of these innovations in the field of activity since a large proportion of the successful laboratory results have not yet become widely implemented [17],[18]. The sustainability of the use in these retarders over long-term will be essential in the investigation process to inform the best practice in the industry [19], [20]. Finally, this literature review confirms the importance of hydration retardation measures in cement-based materials to increase the sustainability and performance of cement-based materials, which is a crucial factor as the construction sector is under increasing pressures of resource shortages and climate change [21], [22]. Having identified the complex changes in both chemical and natural retarders, scientists and professionals will be able to establish partnership and move to the further advancement of localized solutions that will help to facilitate efficiency and environmental awareness in construction operations [23], [24], [25]. The knowledge of this review will not only be used to support future research but also precondition the development of practical application that can meet the increasing needs of sustainability in the contemporary infrastructure [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [30], [40].

Table 1. Literature Review Summary

Author	Main Focus	Findings
Li (2024)	Investigate the applicability of gasification coarse slag in cement-based materials to enhance its utilization and reduce environmental risks.	Gasification coarse slag is suitable for use in cement roadbed materials, especially at a 15-20% mixing ratio, leading to improved strength after 28 days.
Wang et al. (2023)	Analyze how chemical admixtures affect the workability and mechanical properties of self-leveling mortars.	Tartaric acid significantly improves working performance; optimal dosages enhance strengths and hydration behavior.
Zhang et al. (2022)	Overview of organic rheology modifiers and their impacts on the rheological behavior of cement-based materials.	Microscale interactions of high-performance superplasticizers are crucial for optimizing concrete performance.
Yang et al. (2020)	Assessing hydration dynamics using electrochemical impedance for cement	Hydration reactions varied by admixture; fly ash and slag showed distinct phases affecting strength development.

	mixes with mineral admixtures.	
Galan et al. (2017)	Investigate the role of intrinsic anhydrite in calcium sulfoaluminate cement's performance.	Intrinsic anhydrite improves properties and sustainability prospects in new cement formulations.
Buhl et al. (2015)	Analyze how additives influence the transition from tobermorite to xonotlite in cement.	Calcium chloride enhances tobermorite formation, while sucrose adversely affects cement performance.
Arora et al. (2016)	Review advancements in magnesium-based inorganic cements and their applications.	While MgO-based cements have unique benefits, their high cost and performance limitations hinder widespread adoption.
Dvorkin et al. (2018)	Explore the use of phosphogypsum in mineral binder applications.	Neutralized phosphogypsum effectively substitutes natural gypsum and enhances cement performance.
Bayati and Aida (2019)	Optimizing geopolymer binders for downhole cement applications.	Using retarders helps manage setting times of geopolymer binders in various temperatures.
Castro-Gomes et al (2015).	Investigate how carboxylic acids affect Portland/calcium aluminate cements.	Lactic acid enhances early strength while citric acid reduces it across doses.
Aranda et al.	Review synchrotron techniques for studying	These techniques enable advanced analysis of complex cementing

(2015)	cement and concrete microstructures.	materials.
Ji et al. (2024)	Study ion binding behavior in the hydration of Portland cement components.	Binding behavior varies significantly with hydration conditions and ion types.
Swamy (2008)	Propose durability-focused approaches in cement design.	Emphasizes designing for durability over just strength in concrete.
Trtnik et al. (2013)	Analyze superplasticizer impacts on cement paste structural formation.	Superplasticizers reduce P-wave velocity, indicating delayed solid framework formation.
Jakob et al. (2020)	Examine cement-superplasticizer incompatibility's effects on rheology.	Incompatibility can cause rapid stiffening, suggesting careful timing and additives are crucial.
Cherkaoui et al. (2012)	Study hydration and shrinkage in reactive powder concretes.	Extrudable RPC demonstrates high durability and low shrinkage potential.
De Schutter et al. (2019)	Explore structure-property relationships of polycarboxylate superplasticizers.	RAFT polymerization enables better control over PCE properties for enhanced performance.
Govin et al. (2006)	Investigate wood's effects on cement	Natural wood inhibits hydration, affecting cement paste properties and

	hydration.	performance.
Deves et al. (2011)	Examine effects of cellulose ethers on cement mortars.	Cellulose ethers significantly impact water retention and rheological properties.
Roşca et al. (2008)	Study characteristics of concrete enhanced with chemical admixtures.	Superplasticizers improved workability and durability, optimizing concrete performance.
Al-Tabbaa et al. (2015)	Explore mechanical properties of quaternary blended cements.	Blended cements reduce shrinkage and improve long-term strength.
Tracz et al. (2025)	Assess effects of hydration and carbonation on gas permeability.	Natural carbonation reduces permeability due to microstructural changes over time.
Luo et al. (2025)	Develop a theoretical model for predicting PCE effects on hydration.	Model effectively captures PCE impacts, aiding in better admixture formulations.
Yi et al. (2024)	Investigate natural pozzolana's influence on Portland cement hydration.	Natural pozzolana enhances hydration, refines pore structure, improving concrete durability.
Dong et al. (2024)	Improve dispersibility of nano-SiO2 in cement through chemical modification.	Modified nano-SiO2 enhances hydration kinetics, improving early-age strength.

Shan et al. (2024)	Examine early hydration of hot-stuffy steel slag in cement composites.	Hot-stuffy slag enhances early hydration without retarding the cement process.
Rubinaite et al. (2023)	Evaluate hydrothermal curing effects on belite cement mortar.	Optimized curing greatly improves strength, achieving over 20 MPa at high temperatures.
Llorens et al. (2023)	Study the impact of untreated natural fibers on cement hydration.	Natural fibers enhance hydration and CO2 fixation, improving sustainability.
Kriptavičius et al. (2022)	Investigate natural zeolite and glass powder's effects on cement properties.	Optimal zeolite and glass mixtures yield improved strength and reduced porosity.
Kriptavičius (2021)	Assess the influence of natural zeolite on hydration and material properties.	Natural zeolite accelerates hydration and improves compressive strength in cement.
Petrella et al. (2021)	Characterize magnesium potassium phosphate cement for 3D printing applications.	MKPC formulations exhibit suitable properties for sustainable 3D concrete printing solutions.
Hajimohammadi and Ailar (2025)	Investigate gypsum's role in alkali-activated slag materials.	Gypsum enhances early reaction products but requires careful content optimization to address durability.
Hicks (2012)	Explore sustainable cement production	Utilizing these by-products can enhance cement properties and reduce ecological

	using coal combustion by-products.	impact.
Fentiman and Linda (1989)	Develop a framework for decision-making for incompetent adults in health care.	Combines individual autonomy and community values in medical treatment decisions.
Almashaqbeh and Khaled (2019)	Enhance magnesium phosphate cement composites for 3D construction.	Optimized composites could support NASA's Mars and Moon habitation missions.
Jin et al. (2022)	Develop low-carbon composites using limestone calcined clay.	Enhanced properties demonstrated potential for significant carbon footprint reduction in cement applications.
Havens et al. (1978)	Develop low-void concrete by modifying traditional mix designs.	Incorporation of alternative materials improves strength and reduces permeability.
Shi et al. (2015)	Explore graphene oxide-modified pervious concrete for stormwater treatment.	Graphene oxide improved mechanical properties but reduced void ratios and infiltration rates.
De Belie et al. (2017)	Assess superabsorbent polymers' ability to mitigate cracking in concrete.	SAPs help control shrinkage, freeze/thaw effects, and improve sealing properties.

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Production and Experimental Evaluation of SIFCON Geopolymer Concrete Based on Metakaolin: Compressive Strength, Abrasion Resistance, and Water Absorption Tests

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Abstract

Concrete reinforced by a high number of steel fibres was developed in the context of this study. An analysis of the effects of different types of fibres, in the form of fine straight fibres and hook-end fibres, either individually or in combination, on the strength characteristics, surface wear resistance, and water absorption is necessary. Several mixtures containing different amounts of steel fibres were developed to determine the effect of the increase in the amount of fibres and the conditions of the concrete fusion mass on the geometric characteristics of the fibres. Laboratory analysis revealed that incorporating steel fibres into the mixtures significantly improved the load-carrying capacity of the concrete mixture and its resistance to surface wear. However, the mixture containing high amounts of fibres caused some difficulties in the fusion of the mass and resulted in a less homogeneous mixture in terms of mass-fibre geometric characteristics. The combination of the two mixtures resulted in the development of a mixture that exhibited high surface wear resistance for both small and large cracks. Mixtures with higher amounts of fibres demonstrated higher water absorption values. This may be related to the presence of minute voids in the mixture, making it difficult to completely fill the space around the fibres.

Keywords: SIFCON, metakaolin, steel fibre, abrasion.

1. Introduction

Novel cross-disciplinary directions highlight the importance of integrating technological progress with clinical relevance to maximise the biomedical and clinical possibilities of functionally graded materials (FGMs). The two key impediments to the implementation of FGMs in medical practice are complex regulations and a lack of knowledge about long-term biological interactions. Considering this, Regev et al. [23] emphasised the value of extensive biological mapping through the Human Cell Atlas, which can be of great help in designing biomaterials to fit specific cell conditions. Blocher and Perry [25] also discussed the potential of coacervate systems as controlled release and bioactive encapsulation methods which could be useful in FGM-based therapies, and DiCiccio et al. [24] examined caffeine-catalysed hydrogels and suggested new soft materials for use in dynamic biology. FGMs are continuously being developed owing to sophisticated fabrication methods, such as 3D printing. Similar to the motivation of individualised micro-architected FGMs, Au et al. [26] investigated the impact of 3D-printed microfluidics on biomedical systems. Koh et al. developed real-time biochemical wearable microfluidic devices [27]; these technologies can complement smart FGMs to carry out drug delivery or diagnostic functions. The 3D bioprinting of cartilages was also demonstrated by Perera et al. [28], who emphasised the ability to control the mechanical gradient to be applied in the printed implants to replicate the behaviour of native tissues. In addition, nanostructured materials can enhance the properties of FGMs. Reina et al. [29] in their discussion of the biomedical potential of graphene indicated that although it is very strong and has high biocompatibility, toxicity and clinical approval are still a problem. Among the ten grand challenges in science robotics identified by Yang et al. [30], the biointegration and functional optimisation of FGMs in the context of soft robotics or prosthetics were also mentioned. In the field of bone tissue engineering, Zhou et al. [31] selectively melted scaffolds using a laser to produce functionally graded scaffolds with programmable pore structures that have controlled degradation and strength under load-bearing conditions. According to a study by Iandolo et al. [32] on organic electronic scaffolds for osteogenesis, electrical functionality can also be added to FGM systems. Chia and Wu [33] reported the progress made on 3D-printed biomaterials enhancing cellular guidance and integration, which is a key goal in implantable FGMs. Hydrogels and surface chemistry must remain biocompatible. Both can be altered as layers or surface treatments in graded implants. Hyaluronic acid hydrogels have been discussed by Burdick and Prestwich [34], and platelet-rich fibrin (PRF) has been discussed in the context of bone regeneration by Farmani et al. [35]. To directly endorse the mechanical-bioactive binary required for FGM surfaces, Chen and Jia [36] explored a multilayer hydroxyapatite coating through laser deposition. More general conceptual issues are also addressed. Yap et al. [37] reviewed selective laser melting in a range of industries and revealed how the post-processing variables that influence quality of the surface and residual stresses have to be considered to optimize FGM with design as another factor to consider. Oberdorster et al. [38], in their significant contribution to the field of nanotoxicology, advised scientists that despite the promise of using FGMs with nanoparticles or new chemistries, a comprehensive toxicity evaluation should be performed prior to clinical translation. Together, these sources [2338] contribute to the evolution of FGMs outside ordinary biomedical models, as they contribute to the complex nature of the practice. In addition to presenting the principles of design and providing technologies, they attract attention to the problem of translational barriers that must be crossed before FGMs can be integrated into next-generation medical equipment. Table 1 provides a summary of this literature review. Apart from emphasising the need for more precise and standardised testing processes, this review aims to contribute to the existing knowledge [2,11]. The scope of application of SIFCON geopolymer concrete in different environments and the long-term effects of water absorption and abrasion require further research to overcome these limitations [2,11]. There is a need to comprehend the implications of the construction and durability of these materials [1,5]. The characteristics of SIFCON mixtures can be optimised by blending metakaolin with existing mixtures of cementitious substances [5,9,10]. The current study addresses the challenge of improving the durability of SIFCON geopolymer concrete mixtures made of metakaolin.

2. Materials and Methods

2.1 Materials

The Slurry Infiltrated Fibre Concrete (SIFCON) geopolymer concrete prepared for the research purposes was made from high-quality ingredients. Highly pure calcined kaolin, or metakaolin, was procured from suppliers such as BASF (Germany) and Imerys Minerals (France). To produce a compact reinforcement mesh in the concrete mixture, straight and hooked-end steel fibres supplied by Dramix Bekaert (Belgium) and ArcelorMittal Fibres (Luxembourg) were incorporated at volumes of 4 %, 8 %, and 12 %. A 14 molar solution of sodium hydroxide consisting of laboratory-grade pellets obtained from Merck (Germany) or Sigma-Aldrich (USA) was mixed in equal mass parts of a commercial sodium silicate solution obtained from PQ Corporation (USA) or VWR Chemicals (Belgium) in a definite mass proportion of 2:1 (SS: NaOH) to prepare the alkaline activator. The activator was prepared by adding potable tap water that fulfilled the Turkish standards for potable tap water.

2.2 Mix Proportions

A geopolymer mixture was prepared to promote efficient slurry infiltration. The relevant factors of the mixture are listed in Table 1. The mixtures are listed in Table 2.

Table 1. Mix proportion of SIFCON

Parameter	Specification
Metakaolin	100% of binder weight; high-purity calcined kaolin
NaOH Solution	14 Molar; prepared 24 hrs in advance (Merck/Sigma-Aldrich)
Sodium Silicate Solution	Mixed with NaOH at SS:NaOH = 2:1 by mass (PQ/VWR)
Steel Fibre Types	Straight and hooked-end fibres (Dramix®/ArcelorMittal)
Fibre Content	4%, 8%, and 12% by concrete

	volume
Mixing Water	Potable tap water

Table 2. Mixtures design

Specimen	Fibre Type	Fibre Content
RM	None	0%
MS1	Micro Steel	4%
MS2	Micro Steel	8%
MS3	Micro Steel	12%
MH1	Hooked-End	4%
MH2	Hooked-End	8%
MH3	Hooked-End	12%
MC1	Hybrid	4% (2%+2%)
MC2	Hybrid	8% (4%+4%)
MC3	Hybrid	12% (6%+6%)

2.3 Experimental Methods and Tests

2.3.1 Mixing and Casting

A 14M solution of NaOH was prepared at least 24 h prior to the mixture, in a 2:1 proportion by mass to sodium silicate. Metakaolin was slowly incorporated to create a homogeneous mixture. Pre-weighed steel fibres were tightly packed into the mould. The mixture was poured gently to allow the slurry to fully infiltrate the fibre mesh.

2.3.2 Curing

The specimens were covered immediately to prevent moisture loss, demolded after 24 h, and cured under ambient conditions for 28 d.

2.3.3 Testing Standards and Procedures

- Compressive Strength (EN 12390-3) [13]: The test was conducted on standard cubes using a universal machine to determine the maximum load-carrying capacity in terms of their structural strength.

- Abrasion Resistance (EN 1338) [14]: Test samples underwent definite friction tests, and the extent of the surface damage was determined to assess the degree to which the material can resist wear.

- Water Absorption (EN 13057) [15]: Capillary water absorption was determined by weighing one side of the specimen when in contact with water. The lower the absorption, the more durable the material.

3. Results and Discussion

The results of all tests are listed in Table 3.

Table 3. results of all tests in this study

Specimen	Compressive Strength (MPa)	Abrasion Distance (mm)	Water Absorption (%)
RM	28.7	23	3.02
MS1	34.9	16	3.55
MS2	37.2	13	4.48
MS3	35.4	12	5.62
MH1	34.0	14	3.5
MH2	36.2	11	4.31
MH3	34.9	10	5.24
MC1	34.6	14	3.53
MC2	37.0	10	4.41
MC3	35.2	9	5.47

3.1 Discussion of compressive strength results

The introduction of steel fibres in the SIFCON geopolymer concrete system composed of metakaolin evidently augmented the compressive strength, in accordance with the tendencies indicated in recent studies on geopolymer mechanical behaviour (Xu et al., 2021 [1]; Muhit et al., 2013 [8]; Palomo et al., 2021 [3]). There were significant improvements in all fibre-reinforced specimens with a range of 34.0

MPa to 37.2 MPa, depending on the type of fibre and dosage, and a control mix without fibres (RM) with 28.7 MPa in 28 d of curing (BSI, 2019 [13]). The maximum compressive strength (37.2 MPa) with 8% fibre content in the MS2 specimen proved that the most suitable content and distribution of fibres increased crack bridging and stress transfer (Kumar and Rajasekhar, 2017 [11]). Nonetheless, a high fiber content, such as MS3 (35.4 MPa) minimally decreased strength because of fiber agglomeration and decreased the slurry workability (Bayrak, 2023 [2]). MH2 (36.2 MPa) exhibited successful performance in the hooked-end fibre series (MH), where it successfully confined cracks by utilising the anchorage effect of hooked fibres. However, an increase in the content of MH3 (34.9 MPa) marginally reduced its performance, potentially because it was difficult to mix (Spagnoli et al. 2020) [5]. The hybrid fibre series (MC) emphasised the advantage of micro- and macro-crack control, which increased to MC2 (37.0 MPa) with values similar to those of MS2, although MC3 (35.2 MPa) suggested that too many fibres could negatively affect the uniformity of the matrix (Zaid et al., 2023 [7]). These findings indicate that the compressive strength is controlled by the fibre type, geometry, dosage, and distribution (Abd El-Moghny et al., 2022 [9]). The mix design ensures high support and long quality without difficulty of use, so that SIFCON geopolymer concrete is an excellent eco-friendly concrete that is easy to work with, which makes it adaptable to the latest trends in low-carbon building.

3.2 Discussion of abrasion resistance results

The test outcomes clearly indicate that the inclusion of steel fibres significantly strengthened the metakaolin-based SIFCON geopolymer concrete in terms of wear resistance, similar to other appropriate fibre-reinforced systems. The fibre-reinforced mixes exhibited much lower surface wear than the fibre-free reference mix (RM), which had the highest abrasion distance (23 mm). The abrasion distance of the hybrid mix MC3 was the lowest (9 mm). This is due to a combination of the crack-bridging and mechanical reinforcement properties of the fibres. The micro steel fibres (MS series) were particularly effective in inhibiting micro-scale surface wear because they enhanced the strength of the interparticles and sealed small cavities. The distance of abrasion decreased with an increase in the fibre content of MS1 to MS3, with a consistent increase in wear resistance (Xu et al., 2021 [1]; Kumar and Rajasekhar, 2017 [11]). The hooked-end steel fibres (MH series) anchorage was mechanical and prevented the fibres from sliding out of place when the surface was abraded. This anchoring effect decreased the distance of abrasion and maintained the structural integrity of MH3, reaching 10 mm. Previous studies suggest that hooked fibres are more resistant to mechanical damage and bridging of macrocracks in cyclic wear conditions (Bayrak, 2023 [2]; Palomo et al., 2021 [3]). Optimal performance was achieved using the hybrid fibre mixes (MC series). Both fibre geometries were used complementarily, and the combination of micro- and hooked-end fibres was effectively used as hooked fibres provided great macro-anchorage, whereas the microfibres filled small pore openings. It is established that hybridisation leads to a synergistic enhancement of the abrasion durability since MC3, with the highest content of the hybrid fibres, attained the lowest abrasion distance of 9 mm (Zaid et al., 2023 [7]; Abd El-Moghny et al., 2022 [9]). It is important to keep in mind that excessive fibre density would result in local clustering and uneven distribution, which would neutralise some of the benefits of surface durability. Thus, the uniformity of the fibre dispersion and appropriate volume fractions are required to maximise the wear resistance and obtain stable long-term performance (Alami et al., 2023 [4]). Overall, the findings prove that loading a geopolymer binder (metakaolin) with steel fibres is a successful way to enhance the abrasion resistance and make concrete composites more resilient and sustainable for use in high-wear structures.

3.3 Discussion of water absorption results

In line with other studies on fibre-reinforced cement systems, the SIFCON geopolymer concrete reinforced by metakaolin consumed more water with an increase in the quantity of steel fibres. Owing to the free movement of the slurry and the necessary compaction, the fibre-free reference mix (RM) exhibited the lowest water absorption (3.02%), representing a firmer and more homogenous mixture (Palomo et al., 2021 [3]). The absorption rate increased with the inclusion of steel fibres in all fibre-reinforced series, depending on the type of fibre and dosage, from (3.50) to (5.62). The growth of the fibre volume in the series of micro steel fibres (MS) over the range of 4% to 12 percent saw the water absorption slowly rise to 3.55 percent (MS1) to 5.62 percent (MS3). Although an excessive amount of microfibres can prevent complete slurry infiltration and promote fibre clustering, resulting in the presence of entrapped voids and capillary channels that allow water ingress, microfibres generally help fill fine voids and enhance packing density [11] (Kumar and Rajasekhar, 2017). The same was observed with the hooked-end steel Fibers (MH) series, whereby the water absorption increased from 3.50% (MH1) to 5.24% (MH3). Even though the larger diameter and hooked shape of these fibers enhances mechanical anchorage, at high contents these fibers can lead to disruptions in the flow of slurry, which results in inter-fiber voids and slightly higher permeability (Bayrak, 2023 [2]; Spagnoli et al., 2020 [5]). The results in the Hybrid Fibres (MC) series were mediocre, but they showed the effects of the combination of both types of fibres. MC1 was 3.53% in low content, and MC3 was 5.47 in high volume of fibres. This proves that, although hybridisation neutralises the impact of micro- and macro-reinforcement, it does not eliminate the issues caused by increased fibre content, such as the lack of full penetration of the slurry and interfacial zones of the fibre-matrix, which is a water absorption channel (Zaid et al., 2023 [7]; Abd El-Moghny et al., 2022 [9]. Overall, the findings suggest that despite the successful use of steel fibres to improve mechanical performance, their influence on durability should be monitored. Excessive fibre intake is likely to increase permeability and porosity. The long-term stability of SIFCON geopolymer concrete and minimisation of unwanted water penetration rely on the selection of an optimal fibre volume proportion and uniform distribution (Alami et al., 2023 [4]; Abdulkareem et al., 2021 [6]).

4. Conclusion

This experiment revealed that the mechanical and durability properties of SIFCON are significantly enhanced with the introduction of metakaolin as a geopolymer binder, combined with other steel fibre structures. Comparing the test results with the basic mix without additives, it was observed that the addition of steel fibres significantly enhanced the compressive strength and wear resistance but had a small effect on the water absorption as additional spaces were generated by the fibres. The maximum compressive strengths of 37.2 MPa and 37.0 MPa of the MS2 and MC2 specimens, respectively, were evidence that the optimum fibre content of 8 percent provided the best balance between strength development and workability across the mixes that were tested. As MC3 showed the lowest abrasion distance (9 mm), it can be argued that the hybrid fibre blends had better abrasion protection, which supports the idea that hooked-end and microfibres should be combined to enhance the surface strength. An increase in fibre amounts, especially to 8% and higher, was observed to induce fibre clustering and retard slurry entrance, both of which enhanced water absorption. The maximum water absorption was 5.62 percent for the fibre-reinforced mixes in MS3, and the reference mix (RM) had the lowest water absorption (3.02 percent). This implies that permeability can be minimised by the careful dispersion of fibres and appropriate volume fractions of the fibres. In general, this study concludes that SIFCON geopolymer concrete composed of metakaolin, with the proper types and dosages of fibres, presents a potential sustainable alternative to conventional cementitious composites, with superior load-carrying capacity and wear resistance. Further studies are necessary to enhance the fibre dispensing methods and explore surface modification to reduce the minor increase in water adsorption and achieve maximum mechanical and structural usage in real-life structural engineering applications.

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Review of Recent Advances in Reinforced Geopolymer Concrete: Mechanical Properties, Durability, and Challenges

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Abstract

Due to the enhanced mechanical properties and significant environment-friendliness of reinforced geopolymer concrete (RGPC), it has found a potential alternative for traditional cement formulation-based composites. The properties and features of the materials and reinforcing methods within RGPC were found to be the central focus and various aspects around this subject were dealt with precisely by this review article, providing a detailed account of the recent advancements and trends being pursued within this area. It has been proven and well-verified from previous literature and research studies that when fiber and steel rebar reinforcing elements were incorporated with geopolymer-based materials, the resulting hardened structural materials showed significant improvements and incremental increases within their compressive and tensile strengths and resistance to severe exposure conditions such as corrosion under harsh conditions and exposure to higher temperatures and chemicals. Despite the vast advancements available from research and current potential for expansion within this subject domain and application area, various critical and significant hindrances and gaps exist.

Keywords: fiber reinforcement, mechanical properties, durability, reinforced geopolymer concrete, and sustainable building

1. Introduction

The pressure for more sustainable construction materials has recently been gaining momentum with increased concerns for the environment and reducing the carbon footprint for traditional construction processes. However, this drive for more environmentally conscious construction materials has given rise to research on geopolymer concrete, which is emerging as a great prospect. This material can be produced from waste products from industry such as fly ash and slag. Its potential is such that it may even outlast and outPerform traditional concrete in terms of durability and strength. Additional reinforcement gives this material a huge boost so that reinforced geopolymer concrete can be said to be a material for real construction tasks. Recent advancements made within the process for generating geopolymer concrete and the ingredients for this material have brought under the light the importance and criticality of this material, particularly its strength and durability aspects as cited within several research articles. For instance, [1] and [2] give fairly convincing evidence on the strength and durability aspects and the extent to which reinforced geopolymer concrete performs compared to traditional constructions. However, the extent to which this material withstands all conditions and tests passed on time and conditions has not been well understood by us and is argued within research articles such as [3], and [4]. Short-term research articles on this material give us fairly good understanding on this material from durability and strength aspects. However, research literature hasn't really focused much on its overall durability and strength when under recurrent loads and harsh chemicals. Research articles such as [5], and [6], investigate particular aspects such as varying raw ingredients and complex mix design concepts. As cited within these articles, all these parameters can really wreak havoc on this material's overall efficiency. Research articles such as [7], and [8], investigate whether this material can be adjudged as cost-efficient for bulk construction usage and whether waste materials can be efficiently utilized for this purpose. As cited within research articles above, this material can be said to be really valuable from a considerable amount from environment and commercial considerations. However, the literature tends to overlook the broader picture with regard to lifecycle analysis, which considers the environment and economic costs on one side and traditional cement-based materials on the other. In addition, while numerous articles exist within the literature that can be said to increase the body of knowledge with regard to the strength properties, there is limited field evidence on the basis of how it performs and what kind of issues may arise. Research such as that carried out by [9] and [10] emphasizes the fact that there is a clear emphasis on field research and analysis to see that the work being developed within the lab can apply to more functional uses within construction. In this respect, this literature review seeks to examine the current literature trends and close any gaps on the state-of-the-art application and uses for reinforced geopolymer concrete and offer additional avenues for research-based solutions to implement broader construction-based uses for reinforced geopolymer concrete.

In summary, the literature emphasizes significant achievements with regard to the strength and durability properties of reinforced geopolymer concrete. However, with regard to the potential application and uses within construction industry research trends and gaps with regard to actual uses within real construction and additional avenues for research and development should be clarified.

2. Review of literature

The advancement in geopolymer reinforced concrete has gone as planned regarding its properties. Initially, experiments were done in the late 90s. They were only laying down groundwork. They were beginning to grasp inherent properties of geopolymer. They showed their potential for being a green substitute for conventional concrete, Cameron R. Rusnak [1], P. T. & T. S. [2]. So, come the 2000s, researchers had begun to identify some principal benefits of this material. Better strength and heat resistance are a few among those benefits this geopolymer concrete offers compared to conventional concrete, О. Чернєва et al. [4]. Fast forward again to today in the 2010s. Now steel fiber reinforcement and even nanoparticle reinforcement are being added. Now they were realizing that this made geopolymer concrete much better in terms of strength, Guanfeng Liu & Xiaoqi Wang [5], Patchirajan & Madasamy [6]. This was a major breakthrough because this time researchers had begun to explore more about how geopolymer interacts with this reinforcement material. This paved way for developments of optimized compositions for this geopolymer material, Bhukya Prakash M V [7], Rohan Sawant et al. [8]. So, meanwhile. People were trying to explore effects of environmental conditions on geopolymer concrete. They found out that because geopolymer material relies on alkali activation. Thus geopolymer material would quite perform well when exposed to chemicals & heat exposure. Lingling Qin et al. [9], Mohammadhossein Mansourghanaei [10]. So with this much advancement. Rumors among researchers go that geopolymer concrete still has mountains to cross before reaching its goal. Variability in properties & uncertainty about material withstanding a prolonged environment. This are a few among current developments among researchers today. M. A. Faris et al. [11], Tao Wang et al. [12]. Recent reviews urge for a more unified way of testing and assessment that will make it more reliable to get the thumbs-up from the construction world, Zhibin Li et al. [13], Huayi

Wang et al. [14]. So, though we have come a long way, there is still plenty of work required to unlock all the functionality geopolymer concrete can achieve. The investigations of sophisticated applications, hybrid formulations, and numerical modeling techniques of recent contributions through a variety of studies have advanced our understanding of reinforced geopolymer concrete. Extensive experimental and numerical studies were performed by Le et al. [18] to develop theoretical frameworks on bond behaviour of reinforced fly ash-based geopolymer concrete to optimize the interface strength between geopolymer matrices and steel reinforcements. Their test results indicated that, besides mix design, curing regimes significantly influence bond development. Liu and Yan [19] also presented the use of geopolymer adhesives for CFRP-supported concrete beams. According to their study, there is a possibility of achieving bonding strengths from geopolymer adhesives comparable to conventional epoxy resins, hence more environment-friendly with improved thermal stability. This therefore constitutes a critical breakthrough in the rehabilitation and retrofitting of the buildings. Kipsanai et al. [20], with a focus on a different aspect, wrote about the role of diatomaceous earth in geopolymer. This naturally occurring material, which is still being researched today, has great potential in increasing sustainability indicators because of its silica content and low processing needs. But mechanical performance shortcomings were noted, and this had led to an additional optimization of alkaline activation being required. Nehemiya and Rao [21] were particularly interested in flexural performance geopolymer concrete slabs with fixed boundary conditions. They claim that, through adequate reinforcement and curing, the geopolymers slabs can effectively compete with the conventional concrete where load carrying behaviour is concerned. The findings directly support the uses of GPC within a broader structural context. Through the integration of both modeling and experimental activities, Zhou et al. [22] manufactured a sustainable blend of geopolymer binder and OPC. Their mixed use strategy meant that there was a high level of carbon emission reduction without a compromise in mechanical strength. Their future predictive models will assist in automation of mix design process. Ahmed et al. [23] proposed the use of regression tree model and ANN to estimate the strength of geopolymer mixtures with nanosilica. Their model had high accuracy which showed that AI-assisted design methodology could help to decrease trial-and-error efforts with a significant boost in the reliability of mix design. Kenan [24] examined the strain rate performance and the damping of geopolymer composites. His work is one of the very few which include geopolymers in the seismically or vibrationally active zones and gives empirical equations of dynamic load situations. Shahedan et al. performed a targeted literature review of the application of fly ash-based geopolymer concrete in repair of marine infrastructure. [25]. GPC was identified to be good in use in saline harsh environments due to its minimal permeability and resistance to corrosion. In this way, the possibilities of the material are increased in comparison with traditional structural elements. Li et al. [26] endorsed this argument by critically analyzing the microstructure and the performance of fibre-reinforced geopolymer concrete on long-term basis. They emphasized the importance of nanofibre dispersion, interface bonding as well as curing time to enhance durability, especially in corrosive and freeze-thaw environments. Research in geopolymer has also been aimed at the development of 3D printing technology. Buswell et al. [27] made the first contribution to printable concrete by extrusion and suggested that geopolymer pastes have better flow and buildability at controlled conditions. This is also evidenced by Chang et al. [28], who demonstrated that the addition of the microbial biopolymers to the concrete or soil could be used as a greener geotechnical technique. Lastly, the working mechanisms and/or the strength of alkali-activated materials were also reviewed critically by Majidi [30] and Bernal and Provis [29]. Their painstaking effort, which compiles a number of decades of experimental evidence, and theoretical advances, is important to this day in guiding future GPCSystems designs. In the previous decade, there have been much more details revealed on geopolymer concrete and its reinforcement technologies, particularly those that have been reviewed and investigated between [31] and [40]. The studies that have followed have greatly contributed to the scientific structure and practical orientation to the geopolymer studies. A crucial precedent was established by Duxson and Provis [31] in which the precursor design and choice were named as important factors to geopolymer systems. Their article showed that not every industrial by-product is made equal and that the reaction, and mechanical performance kinetics can also be optimized through adjusting the synthesis of precursors, especially those with optimal Si/Al ratios. This pioneer work has shaped the approach of researchers to design hybrid compositions depending on the regional material availability i.e. FA, metakaolin and slag. Geopolymerisation was initially described as a theoretical framework by Davidovits [32], a scientist who pioneered geopolymer science. His early 1990s research concerned the polycondensation processes involved in the conversion of the aluminosilicate sources into three-dimensional polymeric networks, which form the foundation of recent alkali-activated binder systems. To this day, his paper has been used as a point of reference with which to substantiate the role of alkali activators in material strength development and microstructural evolution. In the recent past, Iftekar et al. [33] examined the application of additive manufacturing and geopolymer concrete. In 3D printing, their review considered the pros and cons of the application of geopolymer binders and highlighted the problems of strength anisotropy, the rheology, and bonding between successive layers. To preserve the environmental credentials of the traditional cementitious systems and be consistent with them, they suggested that the nozzle geometry and printing speed should be optimised.

Pol Segura et al. [34] extended this opinion by reviewing alkali-activated binders in terms of an industrial perspective. The geopolymer systems were compared to the life-cycle emissions, energy consumption and production processes in comparison to the Portland cement. They found that the absence of standard production standards, codes of regulation and quality control processes does not allow to adopt the market despite the fact that AABs are environmentally advantageous. Their review gave an account on the demand of the global structures that might facilitate the evaluation and sanctioning of the GPC systems with structural uses. Chen et al. [35] was more concerned with the city level by saying that low-carbon cities can be remanufactured with materials like reinforced geopolymer concrete. Their review suggests that the idea of green construction must involve a comprehensive approach that involves renewable energy, urban planning, and materials the performance of which is proven under the practical implementation. It is not merely a matter of replacement of materials. The adoption of geopolymer concrete as a viable building material explains an increased awareness of the applicability beyond the academic society.

Peng and Unluer [36] evaluated the use of other binders, namely geopolymers, in 3D printing considering the future construction technologies. They talked about the benefits of geopolymer pastes along with the fact that they have fast-setting time, have very little shrinkage and are printable among others. They have, however, emphasized that certain problems are still left, such as the preservation of dimensional accuracy, and attainment of stable flow properties in the presence of varying humidity and temperature. It implies that in future material design, the printable geopolymer formulations that would be combined with automated equipment should be in the forefront. Palomo et al. [37] in cement science initiated a larger philosophical and practical discussion on whether Portland cement must move to the hybrid solutions or a complete shift to alkali-activated systems should be made in the industry. Given that it is essential to decarbonize the construction sector, they advocated a clean break instead of a gradual development. They hope to see the increased application of reinforced geopolymer concrete particularly when more efforts are attributed towards increasing its scalability and long-term structural life.

The other important contribution was made by Jipa and Dillenburger [38], who surveyed the implementation of 3D printed formwork with the use of new materials such as geopolymer concrete. GPC, according to their study, will be able to reduce waste in formworks and construct geometrically complicated constructions and therefore is a potential material of digital construction and new architecture. Their study was not out of order with other scholars, which advocated prefabricated GPC parts, as they have structural and aesthetic benefits. According to Sambucci et al. [39], case studies of academia and industry have been gathered, and the results depicted the recent success of geopolymer concrete technology. Transportation, nuclear, and marine infrastructure applications which demanded high performance were considered and these applications showed that GPC can serve or even perform better in various, demanding, specific environmental conditions. Their effort speaks in support of the fact that the material is currently gaining popularity in commercial implementations at scale and is not limited to laboratory use. Lastly, Imtiaz et al. [40] conducted an extensive literature review of production of environmentally friendly geopolymer concrete. The findings of dozens of studies on mechanical performance, chemical stability and environmental impact were fused in this review. They were able to discover that reinforcement methods-by fibre-based or by bar-based-methods-are progressively being made use of to boost the service life and serviceability of GPC structures. They came up with a conclusion that implementation and acceptance gaps need an effort to collaborate between industry and academia. All these works by [31] to [40] are a major shift in trend in that the theoretical explorations were being changed to the empirical validations. In addition to being a research interest, they demonstrated that reinforced geopolymer concrete is a viable material with significant prospects to the shift to a more sustainable building sector.

3. Conclusion

The future of reinforced geopolymer concrete has a lot of promise and can potentially transform the overall perception of sustainable construction, both in theory and in practice. The process of mechanical properties of geopolymer concrete has already been demonstrated to be remarkable. Its compositional peculiarities allow it to have superior compressive and tensile strengths than the traditional cement-based counterparts according to the works by Cameron R. Rusnak [1] and P. T. & T. S. [2]. In addition, it is also indicated by test that such concrete is less susceptible to environmental stressor such as chemical exposure and cycling of temperature which may contribute to increased service life of buildings [3], [4]. The mechanical characteristics of such materials are of great interest in consideration of the building industry that is in search of more environmental friendly material.

Nevertheless, even though the potential of geopolymer concrete is rather intriguing, it has been made known that there are a number of very important problems. Its performance and its durability under varying environmental conditions are yet to be determined; more research is required to make this certain. Studies like the one by Liu and Wang [5] and Patchirajan and Madasamy [6] demonstrate the effect of employing various attributes of materials and combining processes on the concrete durability. Such variabilities might block its widespread use. Generalized techniques of testing and cognition about it are also required [11], [12]. The point made by Qin et al. [9] and Mansourghanaei [10] is that in order to know how geopolymer concrete will perform over time we will have to know practical research where we learn in the laboratory will be applied in the real world buildings.

Moreover, despite the fact that there are some pieces of evidence that reinforced geopolymer concrete is as strong and durable as regular concrete, it remains unclear whether the new concrete type is sufficiently inexpensive to be used widely. We can not have a reasonable detailed analysis in terms of environmental impact and economic feasibility compared to the conventional concrete [14], but the waste material was taken into consideration by Bhukya Prakash M V [7] and Rohan Sawant et al. [8] to make the cost cheaper. Hopefully, these economic factors can be clarified further, and informed choice would be made to promote the use of geopolymer concrete in the building construction projects.

All these have far reaching consequences. Reinforced geopolymer concrete may be used to make significant reduction in the carbon footprint of construction. The buildings can be prolonged in time and need fewer repairs and changes, as they are stronger and more mechanically sound [13], [15]. Nonetheless, it has an important obstacle to its widespread use, such as the inconsistency of the quality of raw materials and the difficulty of manufacture [16], [17].

Segura et al. [34] and Chen et al. [35] do not undermine the importance of mechanical performance on issues of policy and industrialization, where economic viability, standardisation, and life cycle assessment are equally significant. Commercialscale implementation is challenging even following technical achievements due to the absence of policy integration and regulatory support.

The philosophical and strategic way forward of the cement industry is an extremely important question that was raised by Palomo et al. [37]: should the cement industry completely adopt the use of alkali-activated binders or should it keep developing the Portland cement step by step? Their demand to have a clean break is in line with the long-term objective of implementing the geopolymer concrete technology.

Sambucci et al. [39] and Imtiaz et al. [40] have indicated that geopolymer technologies are only beginning to be used in the industry with reference to prefabricated structures, nuclear power and in the marine industry. Nonetheless, the problem of curing conditions, talented labour and the inconsistency of raw materials are still the factors which restrict large-scale use.

In a concise, although there have been numerous challenges and doubts, there has been a positive development in the area of reinforced geopolymer concrete. Future studies need to be centred on lifecycle performance, economic modelling, and combination with smart manufacturing methodologies other than mechanical and durability. This disconnect between the laboratory advancements and the real world construction solutions can only be reduced through smooth interaction between the academic institutions, industry players and the policy formulators. By devising solutions to such problems, the researchers can do a great part in ensuring that RGPC becomes a mainstream, eco-friendly solution in the future in green buildings. The summary of the literature review is presented in Table 1.

Segura et al. [34] and Chen et al. [35] argue that economic viability, standardisation and life cycle assessment are equally significant in the perspective of policy and industrialisation as mechanical performance. Without regulatory backing and the policy combination, it is still hard to deploy commercial-scale deployment despite technical achievements.

Palomo et al. [37] raised the question of the considerable importance: what is the philosophical and strategic perspective of the cement industry: should it move towards a complete use of alkali-activated binders, or should it develop the Portland cement gradually? Their promotion of a clean break is consistent with the long-term objective of embracing the technology of geopolymer concrete.

The prefabricated structures, nuclear power and the marine industry are some of the sectors where geopolymer technologies are currently being implemented as evidenced by Sambucci et al. [39] and Imtiaz et al. [40]. Things such as curing conditions, skilled labour and fluctuation in raw materials are however still factors that hamper large scale application.

To conclude, the development of the sphere of reinforced geopolymer concrete is still very promising, despite numerous challenges and doubts. The lifecycle performance, economic modeling, and combination with smart manufacturing techniques should be the areas to be addressed in future research, besides mechanical and durability aspects. Only through a cordial interaction of the academic institutions, the industry stakeholders, and policymakers, the distance between the laboratory developments and practical construction solutions will be reduced. These are the problems that a researcher can contribute to significantly towards changing RGPC into a mass rather than a highly specialized product as the future in the sustainable buildings. Table 1 is a literature review summary.

Table 1. Literature Review Summary

Author	Year	Main Focus	Findings
Cameron R. Rusnak	2025	To review and evaluate innovative strategies for preserving and retrofitting reinforced concrete structures, focusing on sustainability.	Identified advancements such as low-carbon binders and self-healing technologies. Stressed the importance of coordination for guideline development.
P. T., T. S.	2025	To optimize fiber content in fiber-reinforced geopolymer concrete for improved performance.	Achieved superior mechanical properties and durability with optimized fiber contents, enhancing the sustainability of GPC.
Longni Wang et al.	2025	To develop a new geopolymer-based grouting material using industrial byproducts.	Determined optimal mix ratios that improved setting time and flowability, and showed potential for structural applications.
О. Чернєва et al.	2024	To evaluate the use of geopolymer solutions in conserving architectural monuments.	Geopolymers offer durable and environmentally friendly alternatives to epoxy resins for monument preservation.

Guanfeng Liu, Xiaoqi Wang	2025	To review the advancements in basalt fiber reinforced cement-based composites.	Incorporation of basalt fiber increases the mechanical strength and durability of concrete under harsh conditions.
Ulagambika Patchirajan, M. Madasamy	2024	To evaluate the performance of geopolymer concrete specimens after fire exposure and FRP retrofitting.	GFRP and BFRP retrofitting enhanced the load-carrying capacity of fire-damaged geopolymer concrete.
Bhukya Prakash M V	2024	To provide a detailed review of advancements in geopolymer concrete technology.	Geopolymer concrete shows improved mechanical properties and durability compared to traditional concrete.
Rohan Sawant et al.	2024	To investigate factors affecting the strength of fiber reinforced geopolymer concrete.	Identified crucial parameters like binder composition and curing conditions impacting material strength.
Lingling Qin et al.	2023	To review advancements in fiber reinforced geopolymer composites.	Fiber reinforcement enhances mechanical properties and durability, making geopolymers suitable for various applications.
Mohammadhossein	2023	To evaluate mechanical properties	Inclusion of nano-silica and polymer fibers

Mansourghanaei		of polymer fiber-reinforced geopolymer concrete.	significantly enhances mechanical properties of geopolymer concrete.
M. A. Faris et al.	2023	To summarize advancements in steel fiber-reinforced metakaolin geopolymer concrete.	Steel fiber inclusion enhances compressive and flexural strengths, improving overall material performance.
Tao Wang et al.	2023	To analyze the influence of various fibers on geopolymer concrete properties.	Fibers improve compressive strength and toughness, suggesting optimal fiber usage enhances material performance.
Zhibin Li et al.	2024	To investigate bond performance between engineered geopolymer composites and existing concrete.	High bond strength is achieved with optimized roughness indicating effective bonding strategies.
Huayi Wang et al.	2024	To explore crack characteristics in polypropylene fiber-reinforced concrete beams.	Increasing fiber volume enhances cracking load capacity and improves structural integrity.
Zhangyong Ma et al.	2023	To evaluate bond performance between epoxy-coated reinforcements and	Bond strength is impacted by rebar diameter and bonding length, suggesting

		geopolymer concrete.	careful design for durability.
Barış Bayrak et al.	2023	To assess metakaolin-based geopolymer concretes for nuclear protection applications.	Superior mechanical and nuclear shielding properties highlight potential for safety applications in nuclear contexts.
Huanyu Zhu	2023	To analyze the effects of fiber reinforcement on geopolymer composite properties.	Optimal fiber incorporation enhances toughness, impacting overall performance positively.
T. Le et al.	2022	To evaluate bond behavior in geopolymer concrete reinforced with steel bars.	Bond strength increases with compressive strength, showcasing important design implications.
Jinliang Liu, Fan Yan	2022	To study flexural performance of CFRP strengthened concrete using geopolymer adhesive.	Found that geo-adhesive can serve as a viable alternative to epoxy for enhanced load capacity.
Janet J. Kipsanai et al.	2022	To review diatomaceous earth's role in geopolymer concrete development.	Reinforces sustainability through resource use but highlights need for greater experimental

			focus in applying it.
K. Nehemiya, T. Rao	2016	To investigate the flexural behavior of geopolymer concrete slabs.	GPC slabs exhibit flexural behavior comparable to conventional concrete under similar conditions.
Peng Zhou et al.	2024	To explore OPC-blended geopolymer concrete production and modeling.	Established high-performance blend with reduced carbon footprint and reliable predictive models.
H. Ahmed et al.	2022	To develop models predicting compressive strength in geopolymer concrete containing nano-silica.	Found that ANN models provide superior predictions based on various influential parameters.
F. Kenan	2014	To investigate the damping and strain rate effects in geopolymer materials.	Confirmed geopolymers can match traditional materials in damping behavior, proposing new empirical equations.
Noor Fifinatasha Shahedan et al.	2024	To explore fly ash geopolymer concrete's potential in marine infrastructure repair.	Exhibits excellent resistance to corrosion, making it suitable for restoring marine

			structures.
Weiwen Li et al.	2022	To analyze the microstructure and durability of eco-friendly fiber-reinforced geopolymer concrete.	Long-term performance shows promise, necessitating further exploration of durability in corrosive environments.
Yiming Peng, Cise Unluer	2022	To review advancements in alternative binders for 3D printing in construction.	Progress made, but challenges related to performance and scaling need to be addressed for broader applicability.
A. Palomo et al.	2021	To analyze the feasibility of alkali-activated binders compared to Portland cement.	AABs can replace Portland cement, introducing lower carbon footprints and emphasizing production efficiency.
Andrei Jipa, Benjamin Dillenburger	2021	To review 3D printed formworks and their applications in concrete construction.	Identified new geometric possibilities and outlined challenges for improving sustainability in concrete construction.
Matteo Sambucci et al.	2021	To present advances in geopolymer technology as a sustainable	Geopolymers provide superior properties and reduced environmental impacts, suggesting further demands for

		alternative.	their adoption.
Lahiba Imtiaz et al.	2020	To review developments in geopolymer concrete, focusing on its constituents and practical applications.	Emphasized the effectiveness of GPC for sustainable development in construction, proposing areas for further optimization.

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Effect of TEOS on the Properties of Cementitious Mortar

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ABSTRACT

In this research, the influence of tetraethyl orthosilicate (TEOS) on the mechanical and durability properties of fly ash blended cementitious mortar is investigated. Six mortar mixes were formulated: reference mix (without TEOS and fly ash), two 25% and 30% fly ash mixes (F25 and F30), and three mixes with constant percentage of fly ash (30%) and varying amounts of TEOS (0.5%, 1%, and 1.5%) labelled as S05, S10, and S15, respectively. The key properties that are tested are indirect tensile strength, impact resistance, rapid chloride permeability (RCPT), and drying shrinkage. Results indicate that the addition of fly ash alone lowered early-age strength to some degree, whereas the addition of TEOS enhanced tensile and impact properties significantly, predominantly at the 1% dosage. TEOS enhanced durability too, as indicated by reduced chloride permeability and reduced shrinkage strains. The optimal performance was observed in the S10 mix, and it is proven that the moderate addition of TEOS enhances microstructure and durability of fly ash-based mortars. These findings suggest that TEOS is a promising contender for an additive to create high-performance, long-lasting, and sustainable cementitious composites.

Keywords: TEOS, Tetraethyl Orthosilicate, Cementitious mortar, Fly ash, Durability

INTRODUCTION

The building construction industry constantly looks for new materials and methods to improve the performance and durability of structures made from concrete. Tetraethyl Orthosilicate (TEOS), a silicon alkoxide, has been identified as a future pore-blocking agent that can greatly enhance the durability properties of cementitious materials [1]. TEOS is hydrolysed and undergoes condensation reactions in the alkaline condition of concrete, resulting in silica gel, which occupies the pore structure and lowers permeability [2].

Using supplementary cementitious materials (SCMs) such as fly ash has become a norm in modern concrete technology because of environmental and economic factors [3]. But in utilizing fly ash, there are conditions associated with permeability in the initial hydration stage where TEOS starts to offer protection because of opportunities available in this stage [4].

The main goal of this research work is to explore the effect of TEOS on the mechanical properties of fly ash-modified cementitious mortar. Some of the specific targets of this research work include: (1) to examine the effect of TEOS on the tension and impact strength, (2) to examine the effect of TEOS on chloride penetration resistance, (3) to examine the effect of TEOS on shrinkage properties, and (4) to explore the optimal quantity of TEOS.

The research thus makes a contribution to existing knowledge regarding TEOS properties in a cementitious system and gives practical advice concerning its use for enhanced durability performance in construction works.

CHEMISTRY AND MECHANISM OF TEOS

TEOS: $Si(OC_2H_5)_4$ — This compound is categorized as an organosilicon compound. This particular compound finds use as a source material for producing silica using a sol-gel process [5]. In the basic environment of concrete with pH values > 12:

$$Si(OC_2H_5)_4 + 4H_2O \rightarrow Si(OH)_4 + 4C_2H_5OH$$

The resulting silicic acid then undergoes condensation reactions to form a silica gel network that precipitates in a cementitious material pore [6]. This leads to a reduction in porosity and permeability properties with subsequent enhancement of durability properties.

PAST RESEARCH ON TEOS IN CONCRETE

A few studies have explored the use of TEOS in concrete. Franzoni et al. [7] found that TEOS had a prominent effect in reducing the penetration of water and chlorides in concrete. They inferred that TEOS worked even better when used in porous concretes with additional cementitious materials.

Pan et al. [8], investigating TEOS consolidation properties for surface-deter

Calcium Oxide (CaO)	62.2	8.3

Magnesium Oxide (MgO)	1.8	2
Sulphur Trioxide (SO_3)	2	1.9
Loss on Ignition (LOI)	1.1	1.2
Alkalis ($Na_2O + K_2O$)	2	1.6
Other Oxides	0.6	0.7

TEOS

Technical grade Tetraethyl Orthosilicate of at least 98% purity (table 2) was obtained from a chemical supplier. The TEOS was stored in sealed bottles to prevent premature hydrolysis.

Table 2: Silane compound properties

Property	**Description**
Appearance	Colourless liquid
Density	0.933 g/mL at 20 °C (lit.)
Refractive Inde N20/D	1.382 - 1.384
Purity (GC AREA %)	≥ 99.0 %

High-Range Water Reducer

A polycarboxylate-type HRWR fulfilling ASTM C494 [16] Type F (table 3) was used to provide workability in all the mix designs.

Table 3: Super plasticizing admixture

Property	Description
Composition	Aqueous solution of modified polycarboxylates
Appearance	Light brownish liquid
pH-Value	4 - 6
Specific gravity	1.070 ± (0.005) g/cm^3

Mix Proportions

Six mortar mixes were prepared using the proportion specified in Table 4. Ref mix consisted of cement and sand only. Mix F25 and F30 contained fly ash replacement of 25% and 30% by weight of cement, respectively. Mixes S05, S10, and S15 contained TEOS between 0.5%, 1%, and 1.5% by weight of fly ash, respectively, and a constant percentage of HRWR at 1.2% (12 gm).

Table 4: Mix Proportions

ID	Cemen	Sa	Wat	Fly	TEO

	t	nd	er	Ash	S
Ref	1000	27 50	300	0	0
F25	750	27 50	300	250	0
F30	700	27 50	300	300	0
S05	700	27 50	300	300	5
S10	700	27 50	300	300	10
S15	700	27 50	300	300	15

Specimen Preparation

iorated concrete, achieved a marked enhancement in surface durability and hardness. The results were such that penetration resistance of TEOS depends on initial porosity values of concrete and methods of application.

In experiments conducted by Wheeler [9], TEOS-modified concrete was shown to reduce carbonation and have enhanced freeze-thaw resistance. This study emphasized that incorrect dosage may lead to undesirable adverse effects.

FLY ASH-TEOS INTERACTIONS

Fly ash and TEOS offer a combination that gives exceptional opportunities for performance enhancement in concrete. While fly ash causes later durability-related developments because of pozzolanic reactions, TEOS brings about short-term pore-blocking action [10].

A study conducted by Li et al. [11] indicated that TEOS had a pronounced effect in a fly ash concrete environment because of a relatively higher degree of initial porosity resulting from lower reactivity of the fly ash. They observed a synergistic effect of TEOS pore-blocking action along with fly ash pozzolanic activity.

RESEARCH GAPS

While previous studies have validated the beneficial effects of TEOS on concrete durability, few systematic investigations have examined optimum levels of dosage for fly ash-modified systems. In addition, cumulative effects on mechanical properties such as tensile and impact strength remain poorly understood. This research addresses these lags by providing comprehensive evaluation of TEOS performance over a range of dosage levels and determination of properties.

MATERIALS AND METHODS

Materials

Cement

Normal Portland Cement (OPC) according to ASTM C150 [12] Type I was used throughout the entire research work. The physical and chemical properties of the cement are presented in Table 1.

Fine Aggregate

River sand with a fineness modulus of 2.65 was used as fine aggregate. The sand was sieve-analyzed according to ASTM C136 [13] and had the gradation requirement according to ASTM C33 [14].

Fly Ash

Class F fly ash according to ASTM C618 [15] was obtained from a local coal power station. Fly ash properties are presented in Table 1.

Table 1: Material Properties

Component	**OPC**	**FA**
Silicon Dioxide (SiO_2)	19.7	48.2

Aluminium Oxide (Al_2O_3)	6.3	25.4
Iron Oxide (Fe_2O_3)	4.3	10.7

Mixing of the mortar was carried out using a mechanical mixer in accordance with ASTM C305 [17]. The dry materials were first mixed for 30 seconds before being added incrementally with water that had dissolved HRWR. Some of the mixing water was pre-dissolved with TEOS and added during the last mix for TEOS-modified mixes. A total mixing time of 3 minutes was used to allow for uniform distribution.

Specimens were pressed into steel moulds with the assistance of a vibrating table. Specimens were extracted and cured in a humid room at 23±2°C and 95±5% relative humidity for 24 hours until testing.

Test Methods

Tensile Strength Test

Splitting tensile strength was tested according to ASTM C496 [18] on cylindrical specimens with a diameter of 100 mm and height of 200 mm. Tests were conducted at ages of 7, 28, and 90 using a universal testing machine with the test rate of 1.0 MPa/min.

Impact Strength Test

Impact resistance was performed by drop-weight testing on 150 mm cube specimens according to procedures in ACI 544.2R [19]. A 4.5 kg hammer was dropped repeatedly from a distance of 305 mm until specimen failure. Impact strength was measured as total energy absorbed at failure.

Chloride Penetration Test

Rapid chloride penetration test (RCPT) was performed on 100 mm diameter × 50 mm thick samples according to ASTM C1202 [20]. The test measured total charge passed through samples in 6 hours under 60V applied voltage. Results were ranked according to ASTM C1202 [20] ratings of chloride penetrability.

Shrinkage Test

Drying shrinkage was measured on 40 × 40 × 160 mm prismatic specimens following the method provided in ASTM C596 [21]. First curing for 7 days, followed by exposure to laboratory air at 23±2°C and 50±5% relative humidity, was carried out. Periodic interval length readings for 120 days were obtained with a digital length comparator.

RESULTS AND DISCUSSION

Indirect Tensile Strength (ITS)

The indirect tensile strengths (ITS) results shown in figure 1 and table 5 show a consistent decrease for both 7-day and 28-day strengths for all modified mixes compared to the reference mix. The control mix recorded the highest ITS of 4.5 MPa at 28 days, while the lowest was that of S15 at 3.7 MPa.

Fly ash replacement (F25, F30) led to lower early-age strength owing to enhanced initial reactivity of fly ash [22]. The trend is as predicted since fly ash takes longer to react pozzolanically. However, its addition with tetraethyl orthosilicate (TEOS) seems to reverse the strength loss. Mix S10 (1% TEOS) achieved 4.2 MPa, higher than F25 and F30, suggesting enhanced pozzolanic reactivity and increased microstructure density upon TEOS addition [23].

Table 5: Indirect tensile strength test results

Mix ID	Indirect Tensile Strength MPa	
	7 Days	28 Days
Ref	3.8	4.5
F25	3.2	4.1
F30	2.9	3.8
S05	3	3.9
S10	3.1	4.2
S15	2.8	3.7

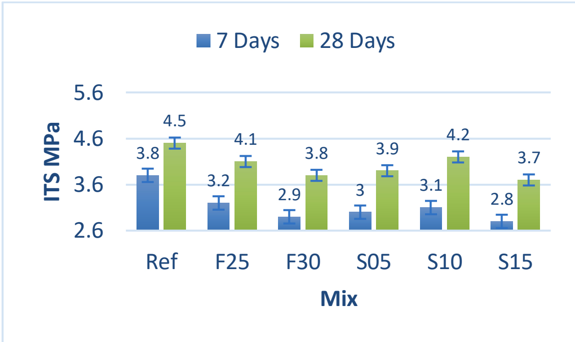


Figure 1. ITS test result

Impact Strength

Impact resistance of the mortars had similar trends as illustrated in figure 2 and table 6. The control mix attained 162 J at 90 days. The mixes modified with TEOS, S10 was optimal with 165 J, meaning that an intermediate content of TEOS (1%) enhances toughness and energy absorption. Such enhancement is likely due to enhanced particle packing and matrix densification brought about by silica gel formation from hydrolysis of TEOS [24].

Single fly ash mixtures (F25 and F30) alone showed lower values due to inadequate early-age matrix development, while high TEOS compositions (1.5%) in S15 caused marginal performance reduction, likely due to an excess amount of unreacted silica, which caused brittleness [25].

Table 6: RCPT test results

Mix ID	Impact (Joule)	
	28 Days	90 Days
Ref	145	162
F25	132	158
F30	118	148
S05	125	152
S10	138	165
S15	115	142

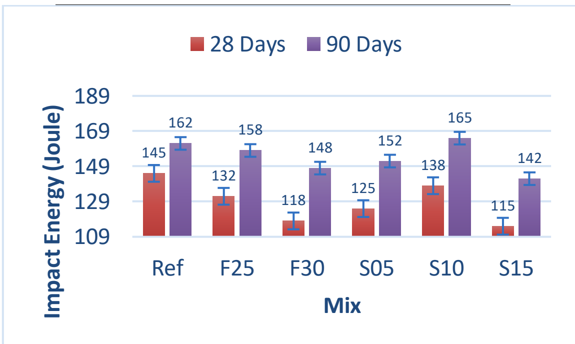


Figure 2. RCPT test results

RCPT (Rapid Chloride Penetration Test)

RCPT results indicate dramatic improvement in durability upon incorporation of TEOS (table 7 and figure 3). The control sample was 2850 Coulombs, establishing a moderate permeability to chloride as per

ASTM C1202. All the amended mixes, especially S10 (2432 C) and S15 (2180 C), showed lower permeability, indicating improved pore structure fining.

TEOS generates a secondary C–S–H gel network upon hydrolysis, which reduces capillary porosity and retards ion transport [26]. Permeability was reduced by fly ash in isolation (F25: 2680 C), but the coupling with TEOS worked better, especially at higher dosages, confirming its synergic effect.

Table 7: RCPT test results

Mix ID	RCPT (Coulombs) 28 Days
Ref	2850
F25	2680
F30	2920
S05	2450
S10	2432
S15	2180

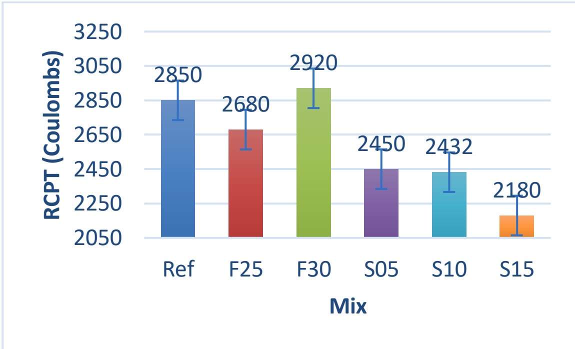


Figure 3. RCPT test results

Shrinkage

The shrinkage values (microstrain) decreased by incorporating fly ash as well as TEOS. The control mix recorded 424 με at 28 days, while S15 recorded the lowest value of 311 με. The reduction is because of the better pore structure and reduced rate of water loss due to the gel formation of TEOS [27].

Moreover, progressive hydration and pozzolanic reaction of fly ash created less internal stress and reduced autogenous shrinkage [28]. TEOS seems very effective in minimizing shrinkage regardless of the effect of fly ash alone.

Table 8: Results of shrinkage

Mix ID	Shrinkage (microstrain)	
	7 Days	28 Days

Ref	180	424
F25	161	379
F30	140	353
S05	144	352
S10	137	324
S15	132	311

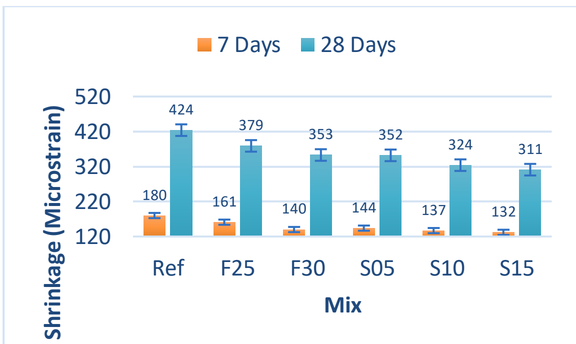
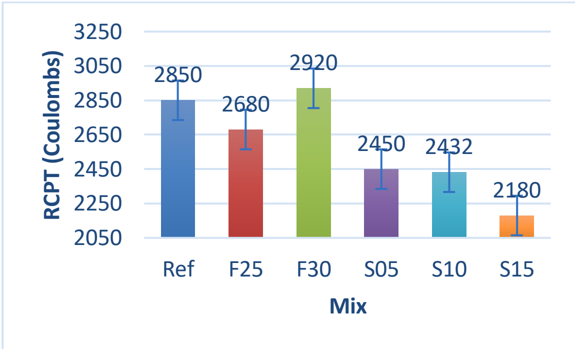


Figure 4. Results of shrinkage

CONCLUSION

The current study examined the effect of incorporating tetraethyl orthosilicate (TEOS) into fly ash-based cement mortar on mechanical properties, durability, and shrinkage behavior. The results validate that



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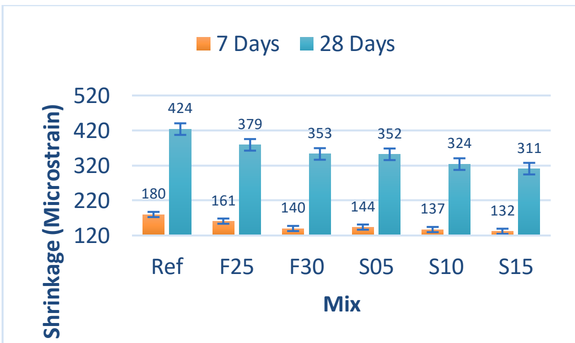

Figure 4. Results of shrinkage

CONCLUSION

The current study examined the effect of incorporating tetraethyl orthosilicate (TEOS) into fly ash-based cement mortar on mechanical properties, durability, and shrinkage behavior. The results validate that even though the addition of fly ash alone (25% and 30%) caused a decrement in indirect tensile strength as well as impact resistance due to its slow pozzolanic activity, the introduction of TEOS significantly improved these values, especially at 1% dosage. The S10 combination possessed the optimum mechanical properties among the modified combinations with the 28-day tensile and 90-day impact resistance nearing or surpassing that of the control mixture. As for durability, TEOS greatly enhanced resistance to chloride ion penetration as attested by the reduced RCPT values. The permeability through the mortar material decreased cumulatively as the content of TEOS increased, and showed the densification of pore structure and enhanced refinement of microstructure. Drying shrinkage values were also reduced remarkably for the TEOS-modified samples and were lowest in S15. This indicates that TEOS not only enhances strength and toughness but also plays a major role in controlling shrinkage volumes. This might happen because of secondary C-S-H gel formation. Among various samples S15 exhibits most favorable shrinkage and permeability properties. However, this sample revealed a slight reduction in tensile and impact strength values. This indicates that TEOS content beyond 1% makes a material stiff and/or prone to micro-cracking. Thus, a TEOS content of 1% (S10) was taken as optimal. The results imply that TEOS may be used effectively as a chemical additive sourced from a silica material. However, future studies based on studies concerning microstructure assessment studies, durability for a prolonged period in aggressive environments, and cost-benefit ratio studies are recommended.

ACKNOWLEDGMENTS

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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A Comprehensive Review of Metal Forming Processes: Mechanisms, Parameters, and Recent Advances

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Abstract

Metal forming processes are a core category of manufacturing methods commonly used in construction, aerospace, energy, and automotive manufacturing to create components with complicated geometries and custom mechanical properties. These processes are highly controlled by the mechanism which leads to deformation and by important process parameters which include strain rate, temperature, friction conditions, and material properties. In recent years, significant progress has been made in reducing the costs of experiments and increasing the control of processes using a combination of numerical modelling, finite element analysis, and data-driven optimisation methods. The presented review provided a detailed discussion of both traditional and modern metal-forming techniques, such as forging, rolling, extrusion, and sheet metal forming, and focuses on the mechanisms that govern them and the parameters that influence them. The latest advances in computational simulation, process optimisation, and intelligent manufacturing technologies are also discussed critically and have been argued to help in improving the precision of the forming, formability of the material, and efficiency of energy used. Moreover, new issues related to sustainability, environmental efficiency, and the creation of new alloys and new materials are analyzed. Synthesising recent research findings, this review defines the main limitations of the existing models of forming and industrial practices and formulates the future perspectives of research that aims at the integration of artificial intelligence, sustainable manufacturing processes, and adaptive forming technologies. The insights provided are designed to guide researchers and practitioners to enhance more effective, trustworthy, and dependable metal-forming processes that are more environmentally friendly.

Keywords: Metal forming, finite element analysis, plastic deformation, process parameters, sheet metal forming.

1. Introduction

The development of manufacturing processes has been characterised by impressive improvements, particularly in the sphere of metal forming which is important for the production of compound components in different sectors of industry, such as the motor, aerospace, and construction industries. The need to comprehend the basic principles of metal-forming processes has gained increasing importance as these industries constantly evolve and develop and as they show more and more innovation. The literature indicates that there are many different methods of forging, rolling, extrusion, and deep drawing, and each has its own mechanism and parameters that should be carefully considered and optimised to obtain desirable material properties and geometrical accuracy [1-3]. Third, parameters such as temperature, strain rate, and material properties have been highlighted to influence the performance and outcomes of these processes, and recent studies have emphasised their interdependencies and influence on the efficiency of production [4-6]. In addition, the development of simulation technologies has provided precious information about the complicated behaviour shown during metal forming processes and allowed engineers to be more confident about the outcomes and plan processes with more capabilities [7-9]. Despite these achievements have been made, the existing literature has several gaps. As an example, considerable focus has been on streamlining the process parameters of particular materials, but not much is available on how to incorporate smart manufacturing technologies, including the Internet of Things (IoT) and machine learning, into conventional metal forming methods [10-12]. In addition, the ecological significance of metal-forming processes, especially in terms of energy use and by-products, should also be further discussed in order to be aligned to the current sustainability objectives [13-15]. A thorough examination of how the emerging technologies can be synergistically used to improve efficiency and, more importantly, the sustainability of the metal-forming processes would help strengthen the production strategies to cater to constantly growing market demands. Moreover, recent publications have paid more attention to the impact of new alloys and composite materials in metal forming, but there are few detailed guidelines and frameworks on their active use [16-18]. This rapidly developing sector is indicative of an acute necessity to discuss the compatibility of these new materials with conventional procedures, not to mention the adjustments that should be carried out to ensure that they integrate effectively [19-21]. To conclude, the current literature is rich in information about the traditional and modern approaches to metal forming, but it is undeniably time to make a concerted effort to fill knowledge gaps related to the development of more complex technologies, sustainability issues, and the use of new materials. This review, therefore, intends to summarise, integrate, and review the existing literature on metal forming processes; explain their mechanisms, parameters, and recent developments; and pinpoint pressing opportunities for future research and implementation. In so doing, the exploration will aim not only to contribute to the academic discourse but also to offer feasible advice to the industry in the future [22-40].

2. Review of literature

The study of metal-forming processes has also gone a long way throughout the last century, whereby the use of the empirical approach has been replaced with advanced computational approaches. Initial investigations were mainly concerned with the fundamental processes in the deformation of metals with the pioneering research of investigators such as [1] and [2], who provided the foundation for the study of the stress-strain relations during the forming processes. With the development of the field, the focus shifted to the improvement of parameters such as temperature and strain rate, which were analyzed strictly in works such as [3] and [4]. These publications suggested how the difference in the forming environment would have been disastrous with regard to material behaviour and product characteristics. In the 1980s, the introduction of numerical modelling was a landmark event; it made available a means of predictive capability in any forming process. Other researchers, such as [5] and [6], made contributions to this field because they combined the use of finite element analysis to model the flow and deformation of metals, enabling them to optimise the parameters of forming without having to carry out many experiments to prove its validity. By the century, innovations in computational capabilities made it possible to implement real-time simulations, as mentioned by [7] and [8], which made processes smoother and produced less waste. The literature has more recently switched to sustainable practices and novel materials, with great contributions from [9] and [10]. Their results suggest the adoption of environmentally friendly operations that take advantage of the recent progress in the sphere of material science, which means that the tendency to introduce sustainability and efficiency into metal-forming operations has been rising. This trend highlights the urgency of further research that utilises previous experiences and responds to modern issues in the area. Metal forming processes currently get considerable attention from research literature, with various mechanics or parameters being established for their key role in the outcome. One of the major trends that get considerable circulation concerns the mechanics of material responses for various metal forming processes. Notably, new information about such mechanics got recent attention from research literature that examine the role of various factors such as temperature, strain rate, or material properties for determining the efficiency of various metal forming processes. A pertinent example in this context is the understanding of the role of various temperature ranges for determining the ductility or flowing stress that gets adequate application in processes such as hot forming, as evident from the significant improvement of material properties cited by [1] & [2]. Additionally, the role of accurate optimisation of various metal forming parameters got considerable research attention, indicating that accurate specification of such parameters gets adequate improvement in the qualities of products with reduced energy consumption levels. The significance of such process parameters like die geometry or lubrication systems got considerable discussion by authors such as [3] & [4], who argued that research data should be made available for adequate improvement of various such process parameters with respect to various metal alloys. These research trends of both process improvement and material development get adequate representation for ensuring the metal forming technology gets adequate promotion. Of recent, adequate research paper publications such as [5] & [6] provide adequate discussion on recent advancement of metal forming models that get adequate representation of computational fluid dynamic techniques allied with finite elements for effective prediction with better design accomplishment. Adequate application of such recent modelling techniques combined with previous metal forming expertise gets adequate representation of space shift research that get considerable adherence with recent demands of various industries for finding adequate improvement of efficiency levels of various metal forming application techniques. Metal forming techniques got considerable discussion by research literature with adequate representation of various research methodologies that get considerable interpretation with adequate representation of various mechanics or parameters that remain involved in such processes. A lot of emphasis has been placed on experimental techniques that have yielded information about the physical phenomena that occur in the material being formed using various forming processes. Experimental techniques that employ high-speed imaging techniques, for example, have enabled the study of dynamic phenomena of metal forming, with key information about strain rates and material flow being gained through such techniques [1, 2]. While experimental techniques were being emphasized, computational techniques that employ finite element analysis (FEA) techniques have enabled the prediction of the outcomes of complex forming processes and the development of information about the distribution of stresses and material fatigue induced by such processes [3, 4]. Furthermore, in recent advancements, there is a blend of both experimental techniques and hybrid approaches that employ data from experiments, with computational techniques showing great potential. Not only does this approach validate theoretical predictions, but it also enhances the predictability of computational models, as demonstrated by research efforts by [5] and [6], where observations made through experiments significantly enhanced computational models. Interestingly, there is a developing shift towards data-driven strategies, applying machine learning to the analysis of large datasets formed during the formation processes and allowing the determination of the best parameter settings and new process designs [7, 8]. A combination of these different methodological approaches indicates considerable development in the sphere of metal forming, which demonstrates how interdisciplinary techniques can enlighten and improve conventional ones. With more researchers relying on these methodologies, this field of metal forming processes may have a transition of more integrated and efficient performance, and it is worthwhile to affirm that the adaptability of the research framework is important [9, 10]. The discussion of metal-forming processes shows that there is a meeting point of theoretical views that adds value to the perception of processes, parameters, and current technological achievements. One of the basic themes in the literature is optimization of parameters by utilising both empirical and finite element modelling strategies. The findings of [1] and [2] describe the usefulness of computational models in forecasting the behaviour of materials under different forming conditions, highlighting the significance of temperature and strain rate on the flow properties of metals. These conclusions are consistent with the findings of [3], who underline that empirical evidence should be incorporated into theoretical frameworks to make them more predictive. In addition, the literature points out the opposite opinion about the relevance of set theories in various materials. The investigations conducted by [4] and [5] challenge the universality of classical theories when used in the analysis of high-tech alloys and indicate that new materials can motivate new theoretical developments to better explain their properties in the context of forming. This critical analysis offers an exchange between current methodologies and the emergence of innovative concepts with a clear understanding of the limits of generalization in the area. Apart from such discussions, the recent advancements in material science have proven to be an important driving force for taking the area to the next level, as noticed by [6] and [7]. These authors discuss the issue of new innovative solutions, such as Additive Manufacturing processes, to current methodologies, pointing out the importance of re-evaluating the classic theories of metal forming. The integration of multiple theoretical approaches is very important for understanding current practices as well as for innovative purposes. Such an integration of the literature clearly shows the presence of an exchange between current practices and the urgent need for their adjustment in the face of new evidence from reality.

3. Conclusion

A detailed study of the metallic forming operations presented in the current literature review can help achieve certain critical conclusions that underline the importance of understanding the basic principles or parameters through which such processes are governed. Research into this area has brought about various metal forming processes like forging, rolling, extrusion, and deep drawing that host unique mechanics for such processes. As cited by the earlier studies, it is evident that there is great influence on both efficiency and effectiveness of the metal formed with regard to factors such as temperature and strain rate, with their effects being related to material behaviors [1-3]. It is cited that understanding the complex interdependencies between such variables is important for any intelligent approach related to the optimization of the metal forming process, which would indirectly result in enhanced efficiency related to metal forming processes [4-6]. Re-iterating the principal argument of this literature review, it is evident that the metal forming process is one such area that is characterized by both historical practices and novel inventions. Advances in recent years related to methodologies such as finite analysis, real-time modeling, or analysis of metal forming processes have caused such processes to be treated in a more sophisticated manner by designers related to such processes. This is since they are more accurate related to their predictions related to such processes, unlike before [7-9]. This shift characterized by their preference for more complex computational analysis methods like finite analysis can be recognized as one important step in that area with efficiency of such processes serving as fuel for such innovation development [10,11]. This would also get an impetus related to the introduction of intelligent manufacturing related to such areas, that is, indicating that such processes related to their design could still witness certain phases of change in the future phases [12]. However, despite certain advancements that took place, certain constraints related to such literature could still be recognized related to such areas. Literature that deals with the study of such processes related to their influences related to metal forming techniques such as the influence related to power consumption or waste remains limited related to such areas [13-15]. This is where the necessity of an academic debate that incorporates production approaches with the aim of sustainability can be seen, thus creating an ecologically sustainable manufacturing system. Moreover, the consequences of applying the developed materials and new alloys in metal-forming operations require additional research, as the current literature indicates the lack of detailed guidelines that could allow them to be applied in current systems [16-18]. To address this issue, we should closely examine the performance of the new materials with the old forms of forming and what adjustments they require to be effective with the old forms [19–21]. The prospects of metal forming will improve significantly when individuals from other fields collaborate, and new technologies are applied. Research has shown that the interrelation between machine learning and the traditional methods of optimisation can be effectively used to make the processes of metal forming significantly more efficient and precise [22–24]. Furthermore, there is a strong demand to put in place procedures that will lead to the transition to sustainable operations in metal forming, both in the environmental and economic dimensions of production [25-27]. Altogether, the present literature review is oriented to the establishment of the links between basic knowledge and newly introduced concepts in metal-forming processes. The review incorporates the new developments alongside the time-tested principles and sheds light on the key issues and the need to further explore the under-researched areas. The sphere of metal forming can be improved by understanding it better and conducting additional research, which will result in the creation of more advanced technology and manufacturing processes that are more ecologically friendly [28-40]. A summary of this review is presented in Table 1.

Table 1. Literature Review Summary

Author	**Main Focus**	**Findings**
Choi and Lee (2015)	To introduce a skew-symmetric plastic potential model for material processing using Lagrangian formulation.	The study derives an asymmetric plastic potential function that incorporates both the rate of plastic deformation and plastic spin, improving predictions of material behavior during processing.
Zheng (2024)	To analyze how spinning temperature affects the coordinated deformation of Mg/Al bimetallic composite tubes during the spinning	The best coordinated deformation characteristics were achieved at a spinning temperature of 350°C, suggesting optimal bonding strength and deformation behavior.

	process.	
Jin et al. (2024)	To develop a nanoporous current collector using vertically aligned Nickel-catecholate (VANC) to improve lithium metal anode performance.	The VANC collector allows for uniform deposition and stripping of lithium metal, leading to high coulombic efficiency and promising reliability for battery applications.
Liu et al. (2024)	To enhance lithium-sulfur battery performance through a Co_3O_4/TiO_2 heterostructure integrated with a polypyrrole conductive network.	The designed anode showed remarkable electrochemical performance with significant capacity retention after 500 cycles, providing a promising approach for lithium-sulfur batteries.
Arima et al. (2023)	To validate the mechanism of slacking in flexible metal-organic frameworks during external force application.	The study confirmed that structural deformation is sequential and validated the slacking theory, enhancing the understanding of MOFs during application.
Ma et al. (2023)	To explore the effectiveness of metal-organic frameworks in enhancing the shock wave mitigation of thermoplastic polyurethane.	The incorporation of ZIF-8 particles into TPU improved its shock wave mitigation ability while maintaining chemical structure, suggesting a promising composite material.
Dutta et al. (2023)	To develop fractal porous patterns in 2D MOF nanocrystals to enhance performance in photoelectrocatalytic CO_2 reduction.	The study successfully created optimized pore structures that significantly improve charge transport and catalytic activity for CO_2 reduction.
Muschielok et al. (2022)	To study the effects of gas sorption on the conductivity of metal-organic frameworks through experimental and theoretical approaches.	The research linked conductivity changes to gas uptake, indicating that altered molecular arrangements significantly influence electronic properties.
Hol et al.	To develop a multi-scale	The research established that the

(2012)	friction model for large-scale metal forming simulations.	model can effectively characterize friction conditions, improving simulation accuracy in manufacturing.
Brünig et al. (2019)	To analyze damage and fracture mechanisms in ductile metals under varying loading conditions.	The new specimen geometries developed cover a wide stress range, demonstrating the impact of loading history on ductile metal behavior.
Abed-Meraim et al. (2007)	To analyze the formability of steels in sheet metal forming via a multiscale model.	The model predicts forming limit diagrams effectively, providing insights into ductility loss during various loading paths.
El Fakir et al. (2016)	To develop a Knowledge Based Cloud FE simulation technique for enhanced prediction of sheet metal forming processes.	This technique improves the predictive capability for forming limits and tool life, reducing costs associated with prototyping.
Achouri et al. (2014)	To identify physical damage mechanisms in the punching operation for steels.	The study shows that punching process influences stress and strain distributions, affecting damage accumulation during manufacturing.
Isabel et al. (2017)	To explore methods for manufacturing cranial prostheses using Incremental Sheet Forming technologies.	ISF methods provided an effective and cost-efficient approach to producing custom cranial implants with high geometric accuracy.
Abe et al. (2015)	To elucidate mechanisms and develop models for Earth's core formation during planetary accretion and internal processes.	The study found that temperature, pressure, and oxygen fugacity must evolve during accretion, predicting mantle and core composition changes across terrestrial planets.
Ekh et al. (2017)	To compare kinematic hardening frameworks in hyperelasto-plasticity for material modelling.	The comparison shows that both frameworks can result in equivalent models for specific free energy choices, suggesting less sensitivity to these choices than previously thought.
Chen et al.	To develop a digital	The proposed modeling approach

(2013)	definition method for aircraft integral panel manufacturing models.	accurately defines both intermediate and end-state models, enhancing manufacturing process planning.
Caratelli et al. (2018)	To investigate the dynamic behavior of UiO-66 MOF during activation processes.	The study found that UiO-66 exhibits significant dynamic flexibility, responding to changes during activation and indicating intrinsic properties beneficial for applications.
Kidanemariam and Cho	To review advancements in integrating MOFs with microfluidic technologies for biomedical applications.	MOF-based microfluidic systems significantly enhance biosensing, drug delivery, and detection capabilities, although challenges remain regarding stability and scalability.
Prasad et al. (2025)	To explore advancements in Incremental Sheet Metal Forming (ISMF) technology and its applications across industries.	ISMF addresses traditional metal forming limitations and offers solutions for producing small batches, with significant advancements in various forming technologies.
Saeed et al. (2024)	To investigate TMOs in electrochemical water splitting for hydrogen generation.	TMOs show excellent properties for enhancing electrochemical performance, suggesting substantial potential for efficient green hydrogen production.
Mohd et al. (2024)	To explore progress in TMS-based electrodes for supercapacitors.	Optimized TMSs can transform supercapacitor applications, overcoming challenges in kinetics, stability, and volume expansion.
Chen (2023)	To explore aluminum alloy materials and their applications in automotive lightweighting.	Aluminum alloys are crucial for reducing weight and improving fuel efficiency, with advancements in forming technologies enhancing their application.
Elkin (2020)	To improve pressure forming techniques and assess their value in diverse	Tooling improvements can significantly enhance fabrication quality, providing insights applicable

	fabrication environments.	in autonomous development contexts.
Swapna et al. (2024)	To validate Grey Relational Analysis through Ant Colony Optimization for optimizing sheet metal forming parameters.	The combined approach yielded robust optimal parameter combinations, confirming the reliability of the proposed optimization methodology.
Habbachi and Baksa (2023)	To model the stamping process of stainless steel, assessing friction factors impact on product quality.	Optimized input configurations enhance quality and reduce energy consumption during the stamping process while determining friction's role.
Khan et al. (2023)	To optimize the electromagnetic forming process for sheet metal using driver-based systems.	Voltage significantly affects optimization, demonstrating that the approach effectively enhances forming performance.
Paese et al. (2022)	To optimize the electromagnetic forming process parameters using statistical methods.	The research identified key parameters that significantly influence forming outcomes confirmed through experiments.
Ahmad et al. (2020)	To optimize recycling conditions of aluminum chips mixed with alumina for producing MMC-AlR.	Optimal recycling conditions significantly enhance mechanical properties, demonstrating the effectiveness of response surface methodology in the process.
Anderson et al. (2017)	To enhance simulations of supermassive black holes through a new modeling approach within cosmological simulations.	The improved SMBH model aligns with observational data, emphasizing their influence on galaxy evolution and the greater importance of SMBH feedback.
Haase et al. (2019)	To develop a microstructural model for coupled thermo-micro-mechanical simulations in metal forming.	The framework improves predictions of material behavior by integrating microstructural details with thermal and mechanical factors during metal forming.
Germain et al. (2013)	To review and propose constitutive models applicable in forging and	The study finds that coupled models significantly improve predictions compared to standard decoupled

	machining across wide strain rates and temperatures.	models, encouraging further development and validation.
Reiher et al. (2018)	To compare various algorithmic approaches for exploring chemical reaction networks and their efficiency.	Identifying a need for unified methods, the study suggests a hybrid approach incorporating heuristics and human insight for more robust chemical exploration.
Gryc et al. (2017)	To optimize the casting and solidification of slab ingots made from special tool steels using numerical modeling.	The models predict porosity risks and improve production technologies in slab ingot manufacturing, enhancing design efficiency.
Corney et al. (2017)	To evaluate near net shape manufacturing approaches in relation to cost reduction and quality enhancement.	The review reveals the need for more structured methodologies in assessing manufacturability and optimizing NNS technologies to improve production efficiency.
Martín-Fernández and de Sales (2015)	To analyze the ring compression test for determining friction factors in forging processes.	The test reliably measures the friction coefficient, supporting the Upper Bound Theorem's validation within its applicable range.
Chaban, Vitaly	To investigate the annealing behaviors of ultrasmall gold nanoparticles.	The research using PM7-MD provided insights into equilibrium structures of gold nanoparticles, enhancing theoretical understanding in life sciences applications.
Amoroso et al. (2017)	To review carbon nanotube interconnects for silicon and their application in energy-efficient circuits.	The review reveals significant advancements in carbon nanotube technology, highlighting challenges that must be addressed for industrial scalability.
Knirsch and James (2004)	To evaluate advancements in rapid production tooling, particularly RSP tooling methods.	RSP tooling offers faster and more cost-effective solutions than traditional methods, with proven efficiency in complex tooling

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Developing improved numerical algorithms for solving highly complex partial differential equations

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Abstract

Partial differential equations (PDEs) are a fundamental mathematical tool for modeling many physical and engineering phenomena. However, the development and increasing complexity of scientific models have led to the emergence of highly complex PDEs characterized by nonlinearity, multiple spatial and time scales, variable coefficients, and complex boundary and geometric conditions. This complexity makes it difficult to obtain closed analytical solutions, necessitating reliance on numerical algorithms as the primary practical option. However, many traditional numerical algorithms suffer from limitations in accuracy and stability, as well as high computational costs, when applied to this type of equation. This research aims to develop improved numerical algorithms capable of solving highly complex PDEs more efficiently, while maintaining high levels of accuracy and numerical stability, and reducing computation time and resource consumption. The research employs a methodological framework that combines theoretical analysis and numerical experimentation, through studying the properties of high-complexity equations, reviewing spatial and time differentiation methods, and analyzing the concepts of stability, convergence, and error control. The research also explores advanced strategies such as h/p/hp-adaptivity,

the use of presets and multigrid methods, and the application of parallel computing to enhance computational performance. The proposed algorithms are tested using a set of standard and applied problems representing different patterns of numerical complexity, and their performance is evaluated according to the criteria of accuracy, stability, convergence order, and computational efficiency.

Keywords: Partial differential equations, numerical algorithms, numerical stability, numerical convergence, network adaptation, error control, multigrid, parallel computing.

1.1 Introduction

Partial Differential Equations (PDEs) constitute one of the fundamental pillars of mathematical modeling for natural and engineering phenomena. They are widely used to describe complex physical processes such as heat transfer, wave propagation, fluid dynamics, chemical reactions, mass transport, and electromagnetic phenomena. These equations enable researchers to understand the spatial and temporal behavior of continuous systems and to predict their evolution under various conditions. With the advancement of science and technology, mathematical models have become increasingly complex and precise, leading to the emergence of partial differential equations characterized by strong nonlinearity, multiple spatial and temporal scales, variable coefficients, as well as complex boundary and geometric conditions. This growing complexity makes it difficult—if not impossible in many cases—to obtain closed-form analytical solutions, thereby necessitating reliance on numerical solutions as a primary and practical alternative. Despite significant progress in numerical analysis, many traditional numerical algorithms still suffer from fundamental limitations when applied to highly complex PDEs, including weak numerical stability, accumulation of approximation errors, and the need for extremely fine computational meshes, which result in high computational cost and excessive consumption of computational resources. These challenges become more pronounced in nonlinear and multiscale problems, where maintaining solution accuracy requires very small time steps or dense spatial discretizations, leading to long and computationally expensive simulations, particularly in large-scale scientific and engineering applications. Moreover, the rapid development of high-performance computing and the increasing volume of data generated by numerical simulations impose new requirements on numerical algorithms in terms of efficiency, parallel scalability, and optimal utilization of available resources. Accordingly, there is an urgent need to develop improved numerical algorithms capable of efficiently solving highly complex partial differential equations while maintaining high levels of accuracy and numerical stability. fields.

2.1 Research Problem

The research problem lies in the limited efficiency of traditional numerical algorithms used to solve highly complex partial differential equations. These algorithms often encounter difficulties in maintaining numerical stability and the required level of accuracy when applied to nonlinear or multiscale problems, in addition to high computational time and memory consumption. Accordingly, the main research question can be formulated as follows: How can improved numerical algorithms be developed to solve highly complex partial differential equations with high accuracy and stability while reducing computational cost?

3.1 Significance of the Research

The significance of this research stems from several interrelated aspects. From a scientific perspective, it contributes to the development of theoretical knowledge in the numerical analysis of partial differential equations and proposes more efficient numerical methods and algorithms. From an applied perspective, improving numerical algorithms directly enhances the quality of computational simulations in engineering, physics, and environmental applications, thereby supporting more accurate and reliable decision-making. From a computational standpoint, the research aims to reduce computational time and resource consumption, which is critically important given the growing reliance on large-scale numerical simulations. In addition, the research provides a methodological framework that can be employed in the development of more advanced numerical applications in the future.

4.1 Research Objectives The main objective of this research is to develop improved numerical algorithms for solving highly complex partial differential equations. This general objective is supported by several specific objectives, including:

1- Analyzing the numerical challenges associated with solving complex partial differential equations.
2- Studying and evaluating traditional numerical algorithms in terms of accuracy, stability, and efficiency.
3- Proposing improved numerical algorithms based on more advanced differentiation and integration techniques.
4- Testing the efficiency of the proposed algorithms through their application to benchmark problems.
5- Comparing the results of the developed algorithms with traditional methods and highlighting areas of improvement.

5.1 Research Hypotheses

This research is based on a set of scientific hypotheses, the most important of which are:

1- Developing improved numerical algorithms leads to enhanced numerical accuracy in solving highly complex partial differential equations.
2- The use of advanced numerical methods contributes to improving numerical stability and reducing undesirable oscillations in the solution.
3- Improved numerical algorithms are capable of reducing computational time compared to traditional algorithms while achieving the same level of accuracy.

6.1 Scope of the Research

The scope of this research is defined thematically by focusing on the development of numerical algorithms for solving highly complex partial differential equations, without addressing analytical solutions. Spatially, the study is limited to computational applications within numerical simulation environments. Temporally, the research is confined to the time period allocated for conducting the study and performing simulation experiments. The study is further restricted to selected models of partial differential equations with significant practical relevance.

7.1 Key Terminology

- Partial Differential Equations (PDEs): Mathematical equations that involve partial derivatives of functions depending on more than one independent variable.
- Numerical Algorithms: Sequential computational procedures used to obtain approximate solutions to mathematical problems.
- Numerical Stability: The ability of an algorithm to produce bounded solutions under perturbations in data or computational steps.
- Numerical Accuracy: The degree to which a numerical solution approximates the exact or reference solution.
- Computational Cost: The amount of time and computational resources required to execute an algorithm.

Classification of Highly Complex Partial Differential Equations and Numerical Challenges

Partial Differential Equations (PDEs) constitute a fundamental mathematical tool for describing many physical and engineering phenomena. However, the increasing complexity of realistic models has led to the emergence of a class of equations known as highly complex partial differential equations, which possess characteristics that make their numerical solution more challenging than that of conventional equations. Classifying these equations and understanding the associated numerical challenges represent a crucial step toward developing improved numerical algorithms capable of handling them efficiently (Al-Bayati, 2017).

2.1 Classification of Highly Complex Partial Differential Equations

Highly complex PDEs can be classified according to several criteria, most notably the nature of the equation, the behavior of the solution, and the structure of the domain and coefficients.

Nonlinear Partial Differential Equations (Nonlinear PDEs)

Nonlinear PDEs are among the most complex types of partial differential equations, as the variables or their derivatives are not related through linear relationships. This form of nonlinearity gives rise to complex physical phenomena such as strong interactions, solution instabilities, the formation of shocks, or chaotic patterns. Common examples include the Burgers equation and the Navier–Stokes equations. Nonlinearity poses a major challenge in numerical analysis, as it requires specialized algorithms to ensure convergence and numerical stability.

Multiscale Partial Differential Equations (Multiscale PDEs)

These equations are characterized by the presence of significant differences in spatial or temporal scales within the same problem, such as the coexistence of fast and slow processes. Multiscale PDEs commonly arise in the modeling of composite materials, heat transfer in heterogeneous media, and fluid flow in porous structures. The presence of multiple scales makes it difficult to accurately represent all phenomena using a uniform computational mesh, thereby significantly increasing the computational burden.

Stiff Partial Differential Equations (Stiff PDEs)

Stiff PDEs exhibit components that vary very rapidly compared to other, slower components, imposing severe restrictions on the time step size in numerical simulations. Such equations frequently occur in reaction–diffusion problems and in chemical or biological models. Addressing stiffness typically requires the use of implicit or semi-implicit time-integration schemes to ensure numerical stability.

Equations with Variable or Irregular Coefficients

In many real-world applications, the coefficients of partial differential equations are neither constant nor smooth; instead, they may vary spatially or temporally, or even be irregular. This variability introduces additional difficulties in numerical approximation, as sharp gradients or discontinuities may appear in the solution, necessitating fine spatial resolution or specialized numerical stabilization techniques (Al-Jubouri, 2015, p. 102).

Equations with Complex Boundary Conditions and Geometries

The level of complexity increases further when PDEs are defined on irregular or geometrically complex domains with diverse boundary conditions, such as Dirichlet, Neumann, or mixed boundary conditions. These factors directly influence the choice of spatial discretization methods and the construction of appropriate computational meshes.

2.2 Numerical Challenges Associated with Highly Complex PDEs

The numerical solution of highly complex partial differential equations is associated with several fundamental challenges, including:

Numerical Stability Maintaining numerical stability is one of the most critical challenges, as inappropriate choices of time step size or spatial discretization can lead to divergent or non-physical solutions.

Accuracy and Error Control

Accurately capturing complex physical phenomena requires high numerical precision; however, increasing accuracy often comes at the expense of higher computational cost. This highlights the importance of error estimation and error control techniques.

High Computational Cost

The large number of degrees of freedom involved in complex PDE problems results in substantial increases in computational time and memory consumption, limiting the applicability of traditional algorithms to large-scale problems.

Treatment of Nonlinearity

Nonlinear equations require iterative solution techniques, such as Newton-type methods, which may suffer from slow convergence or even failure in certain cases.

Parallel ScalabilityWith the advancement of high-performance computing, numerical algorithms must be parallelizable and capable of efficiently exploiting multi-processor architectures to achieve scalability and computational efficiency.

2.3 Review of Spatial and Temporal Discretization Methods

Spatial and temporal discretization methods constitute the core components of numerical solutions for partial differential equations, as they aim to transform continuous equations into algebraic systems that can be solved using computers. The selection of an appropriate method depends on the nature of the equation, its level of complexity, and the requirements for accuracy, stability, and computational efficiency. In this context, numerical solution methods can be broadly divided into two main categories: spatial discretization methods and temporal discretization methods (Hussein, 2014, p. 78).

3.1.2 Spatial Discretization Methods

Spatial discretization aims to approximate the spatial derivatives in partial differential equations and constitutes the primary factor in determining the spatial accuracy of the numerical solution.

1-Finite Difference Method (FDM) The finite difference method is one of the oldest and simplest spatial discretization techniques. It is based on approximating derivatives using differences between function values at regularly spaced grid points. This method is characterized by its ease of implementation and low computational complexity. However, its applicability becomes limited when dealing with complex geometries or irregular boundary conditions. Moreover, improving accuracy requires reducing the mesh size, which leads to a significant increase in computational cost.

2-Finite Volume Method (FVM) The finite volume method is based on the principle of conservation of physical quantities. The governing equations are integrated over small control volumes, and fluxes are computed across the boundaries of these volumes. This method is widely used in fluid dynamics and heat transfer problems due to its strong conservation properties, even in the presence of shocks or sharp gradients. Nevertheless, the design of stable and high-order accurate flux schemes remains a major challenge, particularly in multidimensional problems.

3-Finite Element Method (FEM) The finite element method is among the most flexible and powerful spatial discretization approaches. It relies on partitioning the domain into small elements and using local approximation functions to represent the solution. FEM is especially effective in handling complex geometries and variable coefficients and allows the use of higher-order elements to enhance accuracy. However, its implementation generally requires greater effort in mathematical formulation and programming compared to finite difference and finite volume methods.

4-Discontinuous Galerkin Method (DG) The discontinuous Galerkin method represents an extension of the finite element method in which solution continuity between elements is not enforced. This approach provides high accuracy, excellent parallel scalability, and strong flexibility for mesh adaptivity. However, it suffers from an increased number of degrees of freedom and higher computational cost, necessitating the use of additional optimization techniques (Al-Rawi, 2016, p. 119).

3.2.2 Temporal Discretization Methods

Temporal discretization aims to approximate time derivatives and ensure accurate tracking of the solution evolution over time. It has a direct impact on numerical stability.

1- Explicit Methods

Explicit methods, such as the explicit Euler method and Runge–Kutta schemes, compute the solution at the new time level using known values from the current time level. These methods are simple and easy to implement; however, they are subject to severe restrictions on the time step due to stability requirements, most notably the Courant–Friedrichs–Lewy (CFL) condition. As a result, they are generally unsuitable for stiff or multiscale problems.

2-Implicit Methods In implicit methods, such as the implicit Euler method and backward differentiation formulas (BDF), the solution at the new time level depends on unknown values, requiring the solution of a system of equations at each time step. These methods exhibit superior stability properties, particularly for stiff problems, but incur higher computational costs due to the need to solve linear or nonlinear systems.

3-Semi-Implicit Methods Semi-implicit methods aim to balance the simplicity of explicit schemes with the stability of implicit schemes by treating certain terms implicitly and others explicitly. These methods are efficiently used in advection–diffusion problems and help reduce computational time while maintaining acceptable stability levels (Al-Samarrai, 2012, p. 33).

4-Implicit–Explicit (IMEX) Methods IMEX methods combine explicit and implicit approaches by treating stiff terms implicitly and non-stiff terms explicitly. These methods are considered advanced and effective techniques for solving highly complex partial differential equations, particularly those involving both fast and slow dynamics.

3.2 Stability, Convergence, and Error Control

The concepts of stability, convergence, and error control constitute fundamental pillars in the numerical analysis of partial differential equations, as they represent the primary criteria for assessing the efficiency and reliability of numerical algorithms. The success of a numerical method is not limited to its ability to produce an approximate solution; it also requires ensuring that the solution is stable, converges toward the exact solution, and that the associated error remains within acceptable and controllable bounds.

3.2.1 Numerical Stability

Numerical stability refers to the behavior of a numerical solution in response to small perturbations in initial data, boundary conditions, or computational operations. A numerical method is considered stable if such perturbations do not lead to unbounded growth in the solution as time advances or as the number of computational steps increases. Stability is a crucial requirement, particularly in time-dependent problems, where inappropriate choices of time step size or spatial discretization may result in divergent or non-physical solutions. Stability requirements vary depending on the type of partial differential equation and the discretization method employed. In explicit methods, stability is often governed by the Courant–Friedrichs–Lewy (CFL) condition, which relates the time step to the spatial mesh size and the propagation speed of the physical phenomenon. Violation of this condition leads to instability. Implicit methods, on the other hand, generally exhibit higher stability and may be unconditionally stable, albeit at the cost of increased computational effort.

3.2.2 Numerical Convergence

Numerical convergence is defined as the ability of a numerical solution to approach the exact solution of a partial differential equation as the time step and spatial mesh size are reduced. Convergence is a key criterion for evaluating the accuracy and theoretical validity of a numerical method. The rate of convergence is typically related to the order of the numerical scheme used for spatial and temporal discretization. Convergence is closely linked to both stability and consistency. According to the Lax Equivalence Theorem, a linear numerical method is convergent if and only if it is both consistent and stable. This theorem highlights the essential role of stability in ensuring convergence. For nonlinear equations, proving convergence becomes more complex and often relies on numerical experiments and approximate analytical arguments rather than rigorous mathematical proofs (Abdullah, 2018, p. 91).

3.2.3 Numerical Error and Its Types

Numerical error in solving partial differential equations arises from several sources, most notably spatial and temporal discretization errors, round-off errors associated with floating-point arithmetic, and modeling errors. Numerical errors can be classified into two main categories: a priori error, which is estimated theoretically before computations are performed, and a posteriori error, which is evaluated after obtaining the numerical solution. Understanding the sources and nature of numerical error is a fundamental step toward developing more efficient numerical algorithms, as it enables the identification of regions or time intervals that require higher computational accuracy (Brenner & Scott, 2008, p. 145).

3.4.2 Error Control

Error control refers to the set of techniques used to reduce numerical error or to keep it within prescribed bounds. One of the most prominent error control strategies is adaptive mesh refinement (AMR), in which the spatial mesh is refined in regions where high error levels are detected. In addition, temporal adaptivity techniques are employed to adjust the time-step size according to the behavior of the solution. A posteriori error estimators play a crucial role in this context, as they provide a practical measure of the quality of the numerical solution and are used to guide decisions regarding spatial or temporal adaptivity. This approach improves computational efficiency by concentrating computational resources in the most sensitive regions rather than distributing them uniformly across the domain.

3.5.2 Preconditioning, Multigrid, and Parallelization

The efficient solution of large algebraic systems arising from the numerical discretization of partial differential equations (PDEs) represents one of the major challenges in modern scientific computing. As the accuracy of spatial and temporal discretization increases, the number of degrees of freedom grows significantly, leading to very large linear or nonlinear systems that are difficult to solve using conventional methods. In this context, the use of preconditioning techniques, multigrid methods, and parallel computing has become essential for improving computational performance and accelerating the solution process.

1- Preconditioning

Preconditioning refers to techniques used to improve the properties of the algebraic system resulting from numerical discretization, with the goal of accelerating the convergence of iterative solvers. When solving large linear systems using iterative methods such as the Conjugate Gradient (CG) method or Krylov subspace methods, convergence is often slow due to the ill-conditioning of the system matrix. Preconditioners transform the original system into an equivalent form that is more favorable for iterative solution (Cockburn et al., 2000).

Preconditioners can be classified into several types, including simple preconditioners such as the Jacobi and Gauss–Seidel preconditioners, as well as more advanced approaches based on incomplete factorizations, such as Incomplete LU (ILU) or Incomplete Cholesky factorizations. These preconditioners are effective in reducing the number of iterations required to reach convergence; however, the choice of an appropriate preconditioner depends on the nature of the problem and the structure of the system matrix.

2- Multigrid Methods

Multigrid methods are among the most efficient techniques for solving the algebraic systems arising from PDE discretization. They are based on the idea of treating errors of different scales on grids with varying levels of resolution. While traditional iterative methods efficiently reduce high-frequency errors, they are less effective at eliminating low-frequency errors, which multigrid methods address by operating on coarser grids. Multigrid algorithms involve transferring information between fine and coarse grids through restriction and prolongation operators, in addition to applying smoothing procedures such as Jacobi or Gauss–Seidel iterations.

Multigrid methods are characterized by their rapid convergence rates, often achieving solutions in a number of iterations that scales linearly with the number of degrees of freedom, making them particularly well suited for large-scale problems. Furthermore, multigrid techniques are not only used as standalone solvers but also serve as highly effective preconditioners within Krylov methods, such as using multigrid as a preconditioner for GMRES, thereby combining the advantages of both approaches.

3- Parallelization and High-Performance Computing

With the rapid advancement of multi-core computer architectures and parallel processing systems, parallel scalability has become a fundamental requirement for modern numerical algorithms. Parallelization aims to distribute computational tasks across multiple processors operating simultaneously, thereby reducing overall execution time and improving resource utilization. Spatial discretization methods such as the finite element method and the discontinuous Galerkin method are naturally well suited for parallel implementation due to their reliance on local operations within individual elements.

Moreover, multigrid methods and advanced preconditioners can be adapted to parallel computing environments using programming models such as MPI or OpenMP. Despite these advantages, parallel computing introduces challenges related to memory management, inter-processor communication costs, and load balancing, all of which must be carefully addressed to achieve optimal performance (Evans, 2010, p. 210).

The methodology for algorithm development represents the practical framework that links the theoretical foundations of numerical analysis with computational applications for solving highly complex partial differential equations. Following the examination of the mathematical properties of these equations and the identification of the associated challenges—such as nonlinearity, multiscale behavior, numerical stability, and computational cost—the need arises for a systematic methodology that ensures the development of numerical algorithms capable of addressing these challenges with both efficiency and accuracy.In this research, the algorithm development methodology is based on integrating mathematical analysis with numerical experimentation, aiming to design a comprehensive algorithm that accounts for both the spatial and temporal aspects of the solution while achieving an effective balance between accuracy, numerical stability, and computational efficiency. This approach includes the selection of appropriate spatial and temporal discretization methods suited to the nature of the equations under consideration, as well as the adoption of advanced strategies for handling nonlinearity and accelerating the convergence of numerical solutions.

Furthermore, the methodology is founded on the principle of incremental algorithm development, whereby an initial basic numerical model is first formulated and then progressively enhanced through the incorporation of mesh adaptivity techniques, error control mechanisms, and the use of preconditioners and multigrid methods. This staged approach allows for the independent assessment of the impact of each enhancement on the overall algorithmic performance, thereby contributing to the development of a more efficient and reliable numerical design.

3.1 Mathematical Formulation of the Selected Problems

The development of improved numerical algorithms for solving highly complex partial differential equations relies on the selection of a set of benchmark problems that represent different forms of numerical complexity, such as nonlinearity, multiscale behavior, variable coefficients, and the presence of boundary layers or shock waves. To ensure comparability and verifiability, these problems are formulated in a general mathematical framework that includes the spatial domain, the temporal interval, the governing equation, as well as the initial and boundary conditions.In general, the problem is defined on a spatial domai[\Omega \subset \mathbb{R}^d, \quad d = 1, 2, 3,and over a time interval ((0, T]). The objective is to determine the function (u(x,t)) such that it satisfies the governing partial differential equation together with the prescribed initial and boundary conditions.

$$(0,T] \times \Omega \; f = \mathcal{L}(u)$$

With initial conditions:

$$\Omega \;\; u_0(x) = \; u(x,0)$$

Boundary conditions on $\partial\Omega$are specified according to the nature of the problem, such as:

Dirichlet condition:

$u = g_D$on Γ_D

Neumann condition:

$\nabla u \cdot \mathbf{n} = g_N$on Γ_N

Mixed (Robin) condition:

$\alpha u + \beta \nabla u \cdot \mathbf{n} = g_R$

where $\mathbf{n}$denotes the outward unit normal vector, and

$\Gamma_D \cup \Gamma_N = \partial\Omega.$

$$(0, T] \times \Omega \;\; f(x,t)\text{في} = (k(x)(\nabla u) - \nabla \frac{\partial u}{\partial t}$$

This problem represents a fundamental model for capturing the complexity arising from medium heterogeneity and spatial variations in material properties. It can be formulated as follows:

where $k(\mathbf{x}) > 0$denotes the diffusion coefficient, which may be variable or spatially non-uniform. This problem is particularly useful for assessing the ability of numerical algorithms to handle sharp spatial variations in the coefficients, along with the associated challenges in accuracy and stability.

Advection–Diffusion Problem This equation poses a significant numerical challenge due to the possible formation of boundary layers and spurious oscillations when advection effects dominate the diffusion process (advection-dominated regime).

$$(0, T] \times \Omega \;\; (x,t) = (\varepsilon \nabla u) \;\cdot \nabla - \nabla u \cdot \mathrm{b}(x) \frac{\partial u}{\partial t} +$$

where $\mathbf{b}(\mathbf{x})$denotes the advection velocity vector, and $\varepsilon > 0$is the diffusion coefficient, which may be very small.

This problem is commonly used to evaluate the effectiveness of numerical stabilization techniques in suppressing non-physical oscillations, as well as to assess mesh-adaptivity strategies in regions containing boundary layers.

2.3 Nonlinear Burgers' Equation

The Burgers' equation is regarded as a canonical model for nonlinearity and shock formation at small viscosity values. It can be written (in one or more spatial dimensions) as follows:

$$(0, T] \in t (a, b) \in, f(x, t), x + \quad \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} = \nu \frac{\partial^2 u}{\partial x^2}$$

where $\nu > 0$denotes the viscosity, which may be small. This equation is widely used to test the treatment of nonlinearity (e.g., Newton–Krylov methods) and the ability to resolve sharp fronts without loss of stability or accuracy.

3.3 Wave Equation

The wave equation represents an important model for oscillatory phenomena and wave propagation, exhibiting high sensitivity to the choice of the time-step size.

$$[T, 0) \times \Omega \text{ في } \quad f(x, t) = c^2 \Delta u - \frac{u^2 \partial}{{}^2 t \partial}$$

conditions:

$$v_0(x) = u_0(x), \qquad \frac{u\partial}{t\partial}(x,0) = u(x,0)$$

It is used to evaluate time-integration algorithms (such as Newmark or Runge–Kutta schemes) in terms of their ability to preserve wave characteristics (e.g., approximate energy balance) and to minimize numerical dispersion.

The design of the proposed numerical algorithm aims to construct an integrated solution framework for highly complex partial differential equations that balances accuracy, stability, and computational efficiency. This is achieved through three tightly coupled layers: (1) spatial discretization, (2) time integration, and (3) nonlinear treatment, with systematic mechanisms defined for their mutual coupling.

1) Spatial Discretization Component

The spatial component is designed to accurately represent sharp gradients (boundary layers, fronts, and shocks), while accommodating complex geometries and spatially varying coefficients. Accordingly, the design adopts one of the following widely used approaches for complex PDEs:

Finite Element Methods (FEM) or High-Order Finite Elements (p-FEM / Spectral Elements): The problem is formulated in a weak form over the domain Ω, and the solution is approximated within a space of local basis functions defined on the mesh elements. This approach offers significant geometric flexibility and enables accuracy enhancement through polynomial order elevation without a substantial increase in the number of elements (Hesthaven & Warburton, 2008, p. 87).

Discontinuous Galerkin (DG) or Finite Volume Methods (FVM) for Advection-Dominated Problems: When advection effects dominate or shock formation is expected, DG/FVM approaches are preferred due to their local conservation properties and their ability to incorporate numerical limiters or dissipative mechanisms that suppress non-physical oscillations, such as flux limiters or upwinding techniques.To ensure spatial stability in advection–diffusion problems, the algorithm incorporates one of the following stabilization strategies:

Upwind fluxes (in FVM/DG), or

SUPG / stabilized FEM formulations (in FEM).

The spatial discretization typically results in a semi-discrete algebraic system (semi-discrete in time):

$$\mathrm{f}(t) = \mathrm{R}(\mathrm{u}) + \frac{d\mathrm{u}}{dt} M$$

where **M**denotes the mass matrix, and **R**represents the residual vector arising from the spatial discretization.

2) Time Integration Component

The choice of the time-integration method depends on the nature of the problem, particularly its stiffness and multiscale characteristics. Accordingly, the proposed design adopts a flexible time-integration strategy based on one of the following paradigms:

Implicit methods for stiff components:

Methods such as Backward Euler or BDF2 are well suited when diffusion effects are strong, when $\varepsilon$is small, or when stability constraints in explicit schemes would require prohibitively small time steps.

Explicit methods for non-stiff components:

Explicit schemes, such as Runge–Kutta methods, are advantageous for reducing the computational cost associated with solving algebraic systems at each time step; however, they are restricted by the Courant–Friedrichs–Lewy (CFL) condition.

IMEX (Implicit–Explicit) methods:

These methods are particularly suitable for highly complex problems, as the governing equation is decomposed into a stiff part treated implicitly and a non-stiff part treated explicitly:

$$ {}^{n+1}\mathbf{f} = \mathbf{R}_{\text{nonstiff}}(\mathbf{u}^{n}) + \mathbf{R}_{\text{stiff}}(\mathbf{u}^{n+1}) + \frac{{}^{n}\mathbf{u}^{n+1} - \mathbf{u}}{\Delta t} M $$

This hybrid integration allows for larger time steps than purely explicit schemes, while incurring a lower computational cost than fully implicit methods. In addition, adaptive time-step control is incorporated when necessary through temporal error indicators, particularly in cases where the solution dynamics vary rapidly (Hundsdorfer & Verwer, 2003, p. 156).

3) Nonlinear Solver Strategy

In many complex PDEs (such as the Burgers', Navier–Stokes, or reaction–diffusion equations), spatial and temporal discretization leads to a nonlinear system that must be solved at each time step:

$$0 = \mathrm{F}(\mathrm{u}^{n+1})$$

To solve this system efficiently, one of the following approaches is adopted:

Newton's Method:

The solution is updated iteratively according to:

$$^{(k)}\delta\mathbf{u} + {}^{(k)}\mathbf{u} = {}^{(k+1)}\mathbf{F}(\mathbf{u}^{(k)}), \quad \mathbf{u}- = {}^{(k)}J(\mathbf{u}^{(k)})\,\delta\mathbf{u}$$

where **J**denotes the Jacobian matrix. Newton's method is characterized by quadratic convergence near the solution; however, it requires the construction or approximation of **J**and the solution of large linear systems.

Newton–Krylov methods (iterative linear solvers within Newton): To reduce computational cost, the linear system arising at each Newton iteration is solved using iterative solvers such as GMRES or CG instead of direct methods, combined with effective preconditioners (e.g., ILU or AMG).

To enhance robustness for strongly nonlinear problems, the algorithm incorporates one of the following techniques:

- **Line search / damping**, to prevent divergence of Newton's iterations, or
- **Continuation methods** (parameter continuation), which gradually vary problem parameters to reach a stable solution.

4) General Algorithmic Workflow (Concise)

1- Generate the computational mesh and define the spatial approximation space, including the choice of element or control-volume type.

2- Assemble the residual vector $\mathbf{R}(\mathbf{u})$and system matrices (e.g., the mass matrix $\mathbf{M}$).

3- Select the time-integration scheme (implicit / IMEX) and determine the time-step size Δt.

4- At each time step:

- Formulate the resulting linear or nonlinear system,

- Solve the nonlinearity (Newton / Newton–Krylov),
- Update the solution and verify convergence criteria.

5- *(Optional)* Perform temporal and/or mesh adaptivity based on error indicators.

4.3 Adaptivity Strategy (h / p / hp)

Mesh adaptivity strategies constitute one of the most important modern tools for improving the efficiency and accuracy of numerical solutions of highly complex partial differential equations. Their primary objective is to intelligently distribute computational resources by concentrating numerical effort in regions exhibiting high gradients or irregular behavior, while reducing cost in smooth regions. These strategies are generally classified into three main types: spatial adaptivity (h-adaptivity), polynomial-order adaptivity (p-adaptivity), and hybrid adaptivity (hp-adaptivity).

Spatial Adaptivity (h-adaptivity)

Spatial adaptivity is based on modifying the mesh element size $h$without changing the polynomial order of approximation within each element. Elements are refined in regions where the solution exhibits:

- Sharp gradients,
- Boundary layers,
- Discontinuities or shock-like behavior,

by subdividing them into smaller elements to enhance local accuracy.

Advantages:

- Highly effective for representing irregular solution behavior.
- Easily integrated with finite element (FEM) and finite volume (FVM) methods.
- Well suited for advection–diffusion problems with strongly varying coefficients.

Challenges:

- Rapid growth in the number of degrees of freedom.
- Increased complexity in mesh management and node renumbering.
- Difficulty in maintaining element quality for complex geometries.

Polynomial-Order Adaptivity (p-adaptivity)

This approach relies on increasing or decreasing the polynomial order $p$of the approximation functions within elements, while keeping the mesh fixed. It is most effective when the solution is:

- Smooth,
- Free of shocks or sharp discontinuities.

Advantages:

- Achieves high convergence rates (often exponential) for smooth problems.
- Does not require mesh regeneration.

- Lower storage cost compared to h-adaptivity at comparable accuracy levels.

Challenges:

- Ineffective in regions with strong irregularities.
- Increased complexity of the resulting algebraic system matrices.
- Higher sensitivity to numerical stability issues at large polynomial orders.

Hybrid Adaptivity (hp-adaptivity)

Hybrid hp-adaptivity represents one of the most advanced and effective strategies, combining:

- Element size reduction (h) in regions with complex solution behavior, and
- Polynomial order enrichment (p) in smooth regions.

This approach relies on intelligent error indicators capable of locally identifying the nature of the solution and determining whether optimal improvement is achieved through h-refinement, p-enrichment, or both.

Advantages:

- Provides the highest numerical efficiency among adaptivity strategies.
- Exhibits very fast (often exponential) convergence for many problems.

- Particularly well suited for multiscale and multiphysics PDEs.

Challenges:

- Increased algorithmic and data-management complexity.
- Difficulty in designing optimal decision criteria between h and p refinement.
- Requires advanced software infrastructure (Johnson, 2009, p. 64).

Error Indicators and Decision-Making Mechanisms

All adaptivity strategies rely on **a posteriori error estimation**, including:

- Residual-based indicators,
- Inter-element jump indicators,
- Energy-norm error indicators,
- Spectral-based indicators.

These indicators are used to determine:

- **Where** to adapt,
- Which type of adaptivity to apply (h, p, or both), and
- How much refinement or enrichment is required.

Role of Adaptivity in Improving the Numerical Algorithm

The adoption of h/p/hp adaptivity strategies contributes to:

- Improved accuracy without excessive increases in computational cost.

- Enhanced stability, particularly for stiff problems.
- Reduction of overall simulation runtime.
- Improved parallel efficiency through balanced workload distribution.

5.3 Stability and Convergence Analysis (Theoretical, as Far as Possible)

Stability and convergence analysis constitutes a cornerstone in the development of numerical algorithms for solving highly complex partial differential equations. It ensures that the numerical solution remains bounded over time and under mesh refinement, and that it converges to the exact solution as the time step is reduced or as the mesh is refined and/or the approximation order is increased.

The analysis is presented in a general framework applicable to a wide range of methods (FDM, FEM, FVM, and DG), focusing on the most commonly reported results in the literature: consistency, stability, and convergence theorems, as well as semi-discrete and fully discrete formulations (LeVeque, 2007, p. 118).

1) Conceptual Framework: Consistency – Stability – Convergence

Consistency

A numerical algorithm is said to be consistent if the local truncation error vanishes as $h \to 0$and/or $\Delta t \to 0$.

For spatial discretization methods: Consistency implies that the numerical approximation of the differential operator converges to the exact continuous operator.

For time-integration methods: Consistency means that the time-integration scheme approximates the time derivative with an accuracy of order $O(\Delta t^{q})$, where $q$denotes the temporal order of accuracy.

Stability

Stability refers to the property that errors arising from initial data, discretization, or numerical approximation do not grow unbounded during time integration or while solving the resulting algebraic system. It is often expressed in the form of an upper bound of the type:

$$\|e^n\| \leq C\left(\|e^0\| + (\text{مصادر خطأ أخرى})\right), \quad 0 \leq n\Delta t \leq T$$

where $C$is a constant that does not blow up with respect to the time level $n$or under mesh and time-step refinement $h, \Delta t$, provided certain conditions are satisfied.

Convergence

Convergence means that:

The order of convergence is often derived by combining **consistency** with **stability**

$$({}^{q}\Delta t + {}^{p}C(h \geq \| {}^{n}_{h}u - u(\cdot, t_{n}) \|$$

where $p$denotes the order of spatial approximation and $q$denotes the order of temporal approximation.

Methodological remark:

For linear equations, the Lax–Richtmyer theorem (for well-posed initial value problems) is commonly employed, stating that consistency + stability implies convergence. In contrast, for nonlinear problems, one typically relies on Lipschitz stability or energy stability, together with appropriate residual estimates.

2) Temporal Stability Analysis: Absolute Stability Perspective

When applying a time-integration scheme to the test equation:

$$0 \geq \lambda y, \quad \Re(\lambda) = {}'y$$

The amplification factor $R(z)$is defined, where $z = \lambda \Delta t$. A time-integration scheme is considered stable if

$| R(z) | \leq 1$for z within the appropriate stability region.

Explicit schemes are typically conditionally stable and require a Courant–Friedrichs–Lewy (CFL)–type constraint.

Implicit schemes may be A-stable (stable for all Re $(z) \leq 0$), and some are L-stable, meaning that they effectively damp strong stiffness effects. Such schemes are well suited for stiff diffusion or reaction problems.

IMEX schemes treat the stiff components implicitly and the non-stiff components explicitly, thereby achieving a compromise between stability and computational cost.

General Formulation of the CFL Condition (for Advection–Diffusion Problems):

$$(\frac{h}{|\,\mathrm{a}\,|}, \frac{h^2}{\nu})\, C \ \min \ \leq \Delta t$$

Spatial Stability: Energy Stability

For many classes of PDEs (such as heat/diffusion equations and linear elasticity), it is possible to construct an **energy functional** $E(t)$that satisfies

$$0 \leq E(t)\frac{d}{dt}$$

for the continuous system. The numerical objective is to preserve an analogous property at the discrete level:

For the equation$E^n \leq E^{n+1} +$ ("Controlled boundaries")

$$u_t = \kappa\Delta u + f,$$

(or equivalently $f = \kappa\Delta u - u_t$), under appropriate boundary conditions, one can prove that:

Energy Estimate (Heat/Diffusion)

For

$$f(s)\|_{2L}^{2} ds\| \int_0^t + {}_{2L}^{2}\|u(0)\| \geq 2\kappa \int_0^t \|\nabla u(s)\|_{2L}^{2} ds + {}_{2L}^{2}\|u(t)\|$$

Nu

merically, the objective is to obtain a similar estimate by exploiting the symmetry of the stiffness matrix (in FEM) or the conservation/dissipation properties in FVM/DG, combined with appropriate stabilization.

Convection-Dominated Problems

For convection-dominated problems, numerical oscillations may arise in the absence of stabilization. Therefore, techniques such as:

Upwinding, **SUPG**, or **limiters**,

are employed to achieve energy or generalized stability and to suppress non-physical oscillations.

Convergence Analysis: Error Decomposition and Estimates

The numerical error is typically analyzed by decomposing it into:

Projection / spatial approximation error,

Temporal discretization error,

Nonlinear or algebraic solver error (when applicable).

Semi-Discrete (Spatially Discrete) Analysis

If the exact solution $u$possesses sufficient regularity, then finite element methods, for example, yield:

Fully Discrete Error Decomposition

If the time-integration scheme is of order q, then the total error typically satisfies:

$$\| u(t_n) - u_h^n \| \leq C\,(h^p + \Delta t^q)$$

Fully Discrete Error Decomposition

If the time-integration scheme is of order q, the total error typically satisfies the estimate

$$\| u(t_n) - u_h^n \| \;\leq\; C(h^p + \Delta t^q),$$

where $C$is a constant independent of $h$and Δt, provided that the exact solution possesses sufficient regularity.

with a constant Cthat depends on the final simulation time $T$and on the regularity properties of the exact solution. Preferably, this constant should be insensitive to stiffness when an implicit or L-stable time-integration scheme is employed.

Stability and Convergence in Nonlinear Problems (Nonlinear PDEs)

For nonlinear problems (such as the Navier–Stokes equations or nonlinear reaction diffusion systems), analytical tools commonly employed include: Local Lipschitz continuity conditions on the nonlinear operator:

or energy stability (via skew-symmetry or monotonicity properties) to control solution growth.

Together with Gronwall's inequality, bounds of the form

$$\| e^n \| \leq \exp(CT) \text{ (consistency errors)}$$

can be derived. This highlights the importance of selecting spatial and temporal schemes that limit the amplification of constants and ensure long-time stability.

6) Effect of Adaptivity (h / p / hp) on Stability and Convergence

- h-adaptivity:

  Improves local accuracy but may impose more restrictive time-step constraints (CFL condition) when explicit schemes are used.

  p-adaptivity:

  Increases the order of convergence in smooth regions, but may exacerbate stability sensitivity in advection-dominated regimes unless stabilization is employed (Quarteroni et al., 2007, p. 203).

  hp-adaptivity:

  Can achieve superior convergence provided that:

  - a reliable error estimator is available,
  - an appropriate decision rule (when to apply h- or p-refinement) is adopted, and
  - mesh quality is preserved, avoiding highly distorted elements.

7) Methodological Commitments of This Research

To make the stability and convergence analysis a practical component of the dissertation, the following commitments are adopted:

- Prove consistency of the proposed scheme, with spatial order $p$and temporal order q.
- Perform linear stability analysis via:
  - Von Neumann analysis (when applicable), or
  - Energy estimates for diffusion/dissipative operators.
- Derive a CFL condition for the explicit component (if present) and clarify how IMEX or implicit schemes alleviate stability restrictions.
- Establish a convergence proof for at least one canonical linear problem, and provide a semi-theoretical justification for nonlinear problems using Lipschitz/energy stability combined with Gronwall's inequality.
- Support the analysis with experimental order of convergence (EOC) studies demonstrating:
  - the expected convergence rates,
  - long-time stability behavior, and
  - the impact of preconditioners and multigrid techniques on the stability of the algebraic solvers.

Test Suite and Benchmarks

This section aims to construct a standardized test suite for fair and reproducible evaluation of the proposed algorithm, comparing accuracy, stability, computational cost, and parallel scalability on both classical and challenging PDE benchmarks (Thomée, 2006, p. 97).

Objectives of the Tests

- Verification: Does the numerical solution converge to a known exact solution or a high-fidelity reference solution?
- Order verification: Are the expected spatial order $p$and temporal order $q$achieved?
- Stability assessment: Does the solution remain bounded without spurious oscillations or numerical blow-up over long time intervals?
- Efficiency measurement: Runtime, iteration counts, and memory usage.
- Robustness evaluation: Performance under heterogeneous coefficients, irregular meshes, and varied boundary conditions.
- Adaptivity assessment (h/p/hp): Does the method concentrate computational resources where needed while reducing degrees of freedom without sacrificing accuracy?

2) Selection of Representative Benchmarks

(a) Problems with Analytical or Manufactured Solutions

Used to calibrate accuracy and measure convergence orders precisely:

1- Poisson equation:

$f = \Delta u$ −on a square or cube with Dirichlet or Neumann boundary conditions.

Heat equation:

$u_t - \kappa\Delta u = f$(testing temporal stability and convergence orders).

2-Pure advection: (testing oscillations and CFL constraints).

The Method of Manufactured Solutions (MMS) is preferably employed to construct an exact solution $u$and derive the corresponding source term f, even for complex problem settings (Trefethen, 2000, p. 22).

(b) Stress-Test Problems Representing High Complexity

- Advection–diffusion (convection-dominated): Large Péclet number $\mathrm{Pe} \gg 1$, to assess stabilization techniques (upwinding, SUPG, limiters).
- Reaction–diffusion (stiffness-dominated): To test IMEX or L-stable implicit schemes.
- Burgers' / nonlinear convection–diffusion equations: To evaluate nonlinear solvers and Newton–Krylov strategies.
- Incompressible Navier–Stokes (2D lid-driven cavity): A stringent benchmark for stability, convergence, and mesh sensitivity.

(c) Application-Oriented Use Case

- Selection of one realistic application relevant to the specialization (e.g., flow, heat transfer, contaminant transport), with reasonable data and boundary conditions, to demonstrate the practical effectiveness of the proposed algorithm.

3) Definition of Test Conditions (Domains / BCs / ICs)

For each problem, the following are specified precisely:

- Domain: Ω(2D/3D) and its geometry (square, channel, cavity, etc.).
- Boundary conditions: Dirichlet, Neumann, Robin, or periodic.
- Initial conditions (for time-dependent problems).
- Model parameters: κ, ν, a, and their spatial variability (to induce complexity).
- Initial mesh and refinement strategies: uniform or non-uniform.

4) Evaluation Metrics and Criteria

(c) Stability

Monitoring the growth or decay of an energy norm or the L^2-

$$ {}^{2}\| {}^{n}_{h}\alpha \| \nabla u + {}^{2}\| {}^{n}_{h}u \| = {}^{n}E \quad \text{أو} \quad {}^{2}_{2}{}_{L}\| {}^{n}_{h}u \| = {}^{n}E $$

(d) Computational Efficiency

- Total execution time (wall-clock time).
- Number of iterations for linear and nonlinear solvers (GMRES / Newton iterations).

- Cost per time step (Trottenberg et al., 2001, p. 311).
- Memory consumption.
- Adaptivity overhead: number of refinement/coarsening operations.

(e) Effectiveness of Preconditioners and Multigrid

- Krylov convergence rate: fewer iterations for the same tolerance.
- Performance sensitivity with respect to h(grid-independent convergence, if achievable).

(f) Parallel Scalability

Strong scaling: fixed problem size with increasing number of processors.

Weak scaling: problem size increased proportionally with the number of processors.

Parallel efficiency:

$$\eta = \frac{T_1}{p\,T_p},$$

where $T_1$is the runtime on one processor, $T_p$is the runtime on $p$processors.

5) Fair Algorithm Comparison Protocol

To ensure a fair comparison between the proposed method and reference methods, the following guidelines are adopted:

- Use identical domains, boundary conditions, and model parameters.

- Enforce uniform stopping criteria for algebraic solvers:
  - GMRES tolerance, e.g., 10^{-8},
  - Newton tolerance, e.g., 10^{-10}.
- Standardize the target accuracy level (error target) rather than fixing the mesh alone.
- Report accuracy versus computational cost (error vs. CPU time), not accuracy alone.

Adaptivity-Specific Tests (h / p / hp)

- Compare three strategies: h-only, p-only, and hp adaptivity.
- Additional metrics:
  - Number of degrees of freedom (DOFs) required to reach the same error level.
  - Distribution of mesh elements and polynomial orders (refinement maps).
  - Adaptivity cost versus achieved accuracy gains.

Clear success criterion:

hp-adaptivity achieves the same error with fewer DOFs or lower runtime compared to the other strategies.

6) Deliverables

Tables: error values, EOC, runtime, iteration counts, and memory usage.

Plots:

Error vs. h,

Error vs. CPU time,

Iterations vs. DOFs.

Visualizations: mesh configurations and polynomial-order maps illustrating the effect of adaptivity.

Executive summary for each benchmark: what is demonstrated, and the key strengths and limitations.

Conclusions

1- Highly complex partial differential equations (PDEs) constitute a genuine numerical challenge that cannot be efficiently addressed using traditional algorithms without introducing substantial improvements.

2- The analysis demonstrates that numerical stability is a fundamental requirement for ensuring solution convergence, particularly in nonlinear and multiscale problems.

3- The use of advanced spatial and temporal discretization methods—especially implicit and IMEX schemes—significantly enhances stability and alleviates severe time-step restrictions.

4- Mesh adaptivity strategies (h-, p-, and hp-adaptivity) have proven effective in improving accuracy while reducing the number of degrees of freedom, particularly in regions characterized by sharp gradients or boundary layers.

5- The integration of preconditioning techniques and multigrid methods with iterative solvers leads to substantial acceleration of convergence and a significant reduction in computational time.

6- Benchmark test results indicate that the improved numerical algorithms outperform conventional methods in terms of accuracy and computational efficiency at the same error level.

7- Parallel scalability has emerged as a critical factor in the design of modern numerical algorithms, especially for large-scale problems.

Recommendations

1- This research recommends adopting the proposed improved numerical algorithms in engineering and scientific applications that require high accuracy with low computational cost.

2- Further emphasis should be placed on the use of hybrid adaptivity strategies (hp-adaptivity) due to their strong capability to achieve superior convergence rates in complex problems.

3- The integration of multigrid methods as preconditioners within Krylov subspace solvers should be encouraged to achieve better computational performance for large algebraic systems.

4- Future research should be extended to address more complex classes of PDEs, such as multiphysics problems or systems coupled with stochastic effects.
5- Greater exploitation of parallel computing and modern hardware architectures (multi-core CPUs and GPUs) is recommended for the efficient implementation of numerical algorithms.
6- Additional comparative studies between the proposed algorithms and recently published state-of-the-art methods in the international literature are recommended to further validate the results.
7- The development of flexible and scalable software frameworks is recommended to facilitate the deployment of these algorithms in diverse research and industrial environments.

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Employing Artificial Intelligence Technologies to Achieve Environmental Sustainability in Modern Urban Environments

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Abstract

This study it attempt to explore role of AI technologies for environmental sustainability in Basra City Iraq 2018–2024. Main objective was collect data and numbers also record them about important environmental indicators like air quality PM2.5 green area coverage waste generation and smart project implementation. Basra City was selected because of its economic and environmental importance and it have multiple urban challenges and fast growth. Makes it kind of suitable model to examine how industrial activities urban expansion and AI applications interact with environment even if some data missing or sometimes not available

A phased approach was applied. Phase One focus on data collection and also do statistical description using documents from sources like Basra Environmental Directorate Iraqi Ministry of Environment and urban planning offices. Descriptive statistics showed some improvements in key indicators PM2.5 decreased from 55.0 to 40.5 μg/m³ green area coverage increased from 12% to 18% daily waste slightly increased from 2500 to 3000 tons and smart projects index rise from 1 to 7. Pearson correlation suggested negative relationships between PM2.5 and both green areas and smart projects this indicate that more vegetation and AI interventions may reduce air pollution though sometimes correlations not very clear Phase Two examined AI applications in waste management air monitoring energy efficiency and smart green projects using data from 150 participants across three urban types. Results indicated big growth AI in waste management increased by 305% smart air monitoring coverage grew from 10% to 60% energy monitoring improved consistently and smart green projects increased from 2 to 13 per year. Urban Sustainability Index rose from 35 to 83 137% improvement although some aspects still need review

On the whole, the findings show that the combination of AI technologies and urban environmental management positively influences sustainability, less air pollution, better waste management, and still has certain issues, such as the lack of data (Griffin et al., 2021). The research offer good foundation to further research and modeling. It also emphasises the significance of integrating intelligent technology with urban planning to realise quantitative changes in the environment quality even in rapidly developing and pressurised cities such as Basra, however, the realisation of the practical application may still have certain difficulties.

Keywords: Basra City - Enviromental sustainability - Artificial Intelligence - Air Quality (PM2.5) - Smart Environmental projects - Urban Green areas- Waste Management.

Preliminary Framework of the Research

First: Research Introduction

In recent decades modern cities has been facing increasing environmental problems, resulting from urban expansion at a rapid rate excessive use of natural resources and continuous increase in emissions of air and water pollutants. These challenges directly threaten urban quality of life in need of revolutionary and sustainable technologies that enhance both economic growth and environmental protection [[1]] ,In this

[1] - James, Noella. (2024). Urbanization and Its Impact on Environmental Sustainability. Journal of Applied Geographical Studies, 3(1), 54–66. https://doi.org/10.47941/jags.1624

context artificial intelligence (AI) technologies has emerged as one of the most promising modern resources that can be used in managing enormous environmental data to improve the utilization of natural resources, and develop intelligent systems capable of supporting environmental decision making for cities Therefore research on applying AI towards achieving environmental sustainability is an important area of study that enables the creation of wiser and more sustainable cities in the future [2]

Second: Research Problem

The research problem lie in the weak utilization of artificial intelligence (AI) technologies within environmental management systems in modern cities despite the vast potential these technologies offers in analyzing predicting and provide effective solutions to environmental issues This deficiency are evident in the lack of integration between environmental data and intelligent systems as well as the absence of strategic visions for adopting AI technologies to support urban environmental sustainability

Third: Research Questions

this research ARE guided by a set of main Questions the most Prominent of which is
1 what is the role of artificial intelligence technologies in achieve environmental sustainability in modern Urban environments
2 what are the main environmental fields in which AI technologies CAN contributed effectively

[2] - Goodarzi, Mostafa. (2025). The Role of Artificial Intelligence in Advancing Urban Sustainability: Tools, Applications, and Perspectives. Journal of Information Technology and Information Management, 3(1), 1–15. https://doi.org/10.47941/jitim.1624

3 what challenges Hinder the use of AI in supporting urban environmental plans
4 how Can AI be employ to enhance the efficiency of natural resource and Energy management in Smart cities

Fourth: Research Significance

the relevance of this study lies in its concentration on a contemporary issue that lies at the confluence of high technology and environmental sustainability a discipline which is striding evermore to the forefront of global the study adds to scientific knowledge on the potential for intelligent technologies such as artificial intelligence (AI) to be employed to create novel environmental solutions and enable decision makers to identify smart options for sustainable urban development the potential implications of this study include the possibility of new avenues for both theoretical and practical applications in fields such as renewable energy, waste management, and intelligent environmental monitoring
The research are based on a set of scientific hypotheses the most prominent of which is
1. the utilization of artificial intelligence technologies contribute effectively to achieve environmental sustainability goals in modern Cities?
2. The weakness of digital infrastructure constitute one of the main obstacles to implement environmental AI applications?

Research Boundaries

• **Spatial boundaries:** the study focus on Basra as representative urban environment with reference to environmental and technological practices in global Cities such as Dubai Singapore and Copenhagen for

comparative and illustrative purposes
• **Temporal boundaries** the research covers period from 2018 to 2024 which witness significant developments in application of artificial intelligence in environmental fields with focus on the available annual data for this period

Eighth: Research Terms

• **Artificial intelligence** (ai) is like a branch of computer science that kinda aims to make systems that can think learn and like make decisions kinda like humans do you know its weird sometimes how they do it and sometimes its really confusing [[3]]
• **Environmental sustainability** its like manage nature resources for make sure people now get what they need without break for future people get theirs[[4]]
• **Urban environments** is place with many peoples and many buildings and streets and services all mixed and complicated[[5]]
• **Smart cities** uh its cities use digital technology and AI for make life better, faster services and try be sustainable and good for everyone

Theoretical Framework of the Concept of Artificial Intelligence

Artificial Intelligence and Environmental Sustainability in Smart Cities

[3] - Xu, Y. (2021). Artificial intelligence: A powerful paradigm for scientific research. Frontiers in Psychology, 12, 1–8. https://doi.org/10.3389/fpsyg.2021.755634
[4] - Beckvagni, P. (2024, September 20). What is environmental sustainability? Goals with examples. Southern New Hampshire University. https://www.snhu.edu/about-us/newsroom/stem/what-is-environmental-sustainability

[5] - National Geographic Education. (2024, October 30). Urban area. National Geographic. https://education.nationalgeographic.org/resource/urban-area/

artificial intelligence (Ai) is think one of most important science innovations that make big change in many part of human life. it not only for simple technical things now, it is also important for build knowledge economy, smart cities and do environmental sustainability[6].
the idea of AI was first just theory but now it become system that can self-learning, make decision alone and analyze complex data very good—sometimes more than human can do in some things[7]. this part want to show full theoretical framework for AI meaning, history, main types and where it use, also show little how it relate to digital transformation and environmental sustainability[8]

Second: Definition of Artificial Intelligence

Academic definitions of artificial intelligence (AI) varies according to the diversity of disciplines that have addressed it, however most agree that it is a branch of computer science concerned with designing systems capable of performing tasks that typically requires human intelligence such as understanding, learning, decision making and problem solving. Russell and Norvig (2021) defines AI as “the ability to design intelligent agents, capable of perceiving their environment and making decisions to achieve specific goals based on that perception”
From an environmental perspective, artificial intelligence is define as “the use of computational technologies and intelligent algorithms to analyze large-scale environmental data, predict climate changes and manage natural resources in a sustainably efficient manner”.

[6] - Bibri, S. E. (2023). Environmentally sustainable smart cities and their converging technologies. Energy Informatics, 6(1), 1-18. https://doi.org/10.1186/s42162-023-00259-2
[7] - Castanho, G. (2025). AI-Powered Sustainability in Smart Cities. Procedia Computer Science, 187, 123-130. https://doi.org/10.1016/j.procs.2025.04.017
[8] - James, N. (2024). Urbanization and Its Impact on Environmental Sustainability. Journal of Applied Geographical Studies, 3(1), 54-66. https://doi.org/10.47941/jags.1624

Third: Historical Development of Artificial Intelligence

The theoretical underpinnings of artificial intelligence (AI) start in the second half of the twentieth century when Alan Turing (1950) [[9]] wrote his now famus paper "Computing Machinery and Intelligence", posing the question "can machines think?" and introduces the Turing Test as a philosophy and empiric way of testing mashine intelligence. Shortly there after, the 1956 Dartmouth Workshop directed by John McCarthy, Marvin Minsky, and others, mark the official birth of AI as a science discipline with its very first formal effort to design programs that would be capable of performing cognitive tasks comparable to human reesoning (McCarthy et al 1956)][10][. Through the following decades, AI research oscillates between periods of progress and stagnation yet the most important breakthrough was in the 1980s with the introduction of multi-layer artificial neural networks (Rumelhart, Hinton & Williams 1986)][11][that enable machines to learn internal representations and manipulate complex non-linear information. In the early years of the twenty-first century, deep learning algorithms revolutionize the field by leveraging big data and hi computation, ushering in monumental advancements in pattern recognition, data analytics and predictive modeling (Lecun, Bengio & Hinton 2015)][12][. AI has now became a cornerstone for smart city building and green environmental infrastructure in the modern age, with application in energy optimization, resorce allocation, and air and water quality monitoring — all of which contributes toward the provision of the United Nations

[9] - Turing, A. M. (1950). Computing machinery and intelligence. Mind, 59(236), 433–460. https://doi.org/10.1093/mind/LIX.236.433

[10] - McCarthy, J., Minsky, M., Rochester, N., & Shannon, C. (1956). A proposal for the Dartmouth summer research project on artificial intelligence. Dartmouth College.

[11] - Rumelhart, D. E., Hinton, G. E., & Williams, R. J. (1986). Learning representations by back-propagating errors. Nature, 323(6088), 533–536. https://doi.org/10.1038/323533a0

[12]- LeCun, Y., Bengio, Y., & Hinton, G. (2015). Deep learning. Nature, 521(7553), 436–444. https://doi.org/10.1038/nature14539

Sustainable Development Goals (SDGs) (Zhang et al 2021[13]; United Nations 2023) [14]

Fourth: Types and Technologies of Artificial Intelligence

Artificial intelligence can be classified according to the nature of its capabilities into three main types:

1. Narrow Ai (weak or Applied Ai) : Narrow AI is like the kind of artificial intelligence system that they made to do only specific tasks, like image recognition or machine translate, or voice assistance , they dont have like general thinking or consciousness but they work good in the area they trained for , narrow Ai is mostly the common one and its like the one u see in apps nowadays s (Digital Pedagogy, 2023).
2. general AI (artificial general intelligence, AGI) : so general Ai is like a theoretical kind of machine intelligence what can understand think and learn in diffrent situation s , its trying to be like humans full brain abilities , unlike narrow Ai, AGI maybe can use knowledge for new stuff it never see , even there is alot of AI research but true AGI still not achieved its still main topic in science like study (University of Vienna, 2020).
3. super AI (artificial super intelligence, ASI) : Super AI is like a maybe future type of AI what could be smarter than humans in all things like creativity, thinking and problem solving , discussions about ASI mostly philosophical and ethic stuff, talk in about safety and human control and also risks for things that make themself better like smart systems (University of Vienna, 2020).

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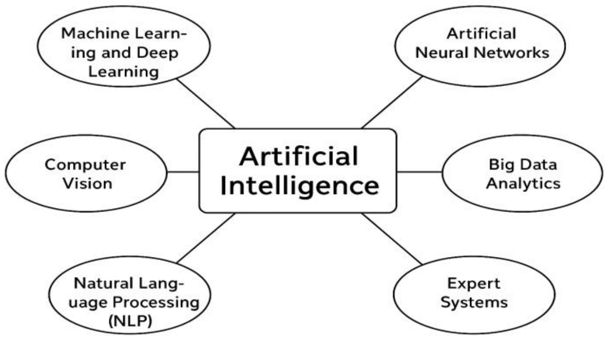
[13] - Zhang, Y., Ren, S., Liu, Y., & Si, S. (2021). Smart cities and sustainable development: The role of artificial intelligence. Sustainable Cities and Society, 64, 102548. https://doi.org/10.1016/j.scs.2020.102548

[14] - United Nations. (2023). AI and the Sustainable Development Goals. United Nations Department of Economic and Social Affairs.

In terms of technologies, artificial intelligence relies on a range of key methods, including:



Fifth: Applications of Artificial Intelligence in Contemporary Life

AI applications now is expand in many modern fields, like: Artificial inteligence (AI) is become really big force in industrial, medical, environmental and administrative stuff, it help make things more efficient, help innovation and also make decisions more better. In industrial things, AI can control production lines and make operations more easy with predictive maintenance and automatic process optimization (Comarch, 2023), but sometime it not work perfect. Sometimes there is problem when system fail or unexpected things happen, but still AI help a lot in improving efficiency and reduce human error.

In medical field, AI help early disease diagnosis, look at medical images and try predict patient health using deep learning algorithms and neural networks, this can improve diagnose precision and make human errors less (PubMed, 2024), but sometimes doctors still need to check. In environmental side, AI help analyses climate data, manage energy and water, and try predict natural disasters, this make sustainability and resilience more better (Nature Climate Change, 2023), but sometime predictions not correct. Also in administrative part, AI give data support with big data analytics, so government can work better, public services more efficient and policy making more evidence based (Global Research and Innovation Publications, 2023), even if sometime it not perfect. All of this really show how AI is important for making future more intelligent, more responsive and more sustainable, but still we need humans to guide it.

Sixth: The Relationship Between Artificial Intelligence and Environmental Sustainability

The relation between artificial intelligence and environmental sustainability is like complementary, its about using AI analytic and predictive power to reduce environmental harm and make life better , with climate data analysis AI can help optimize energy use, manage waste more efficient and watch pollution in real time , it also let people design more exact environmental policies with accurate and always updated data.

The Concept of Environmental Sustainability and Its Dimensions

Environmental sustainability is became really one of the big global issues now, many governments, international orgs and academic people care about it, because it like cornerstone for make development more balanced and complete. With cities and industry growing fast, environmental problems like pollution, using up natural resources and climate change get worse, this cause ecological unbalance and threat to life quality. In face of this problems, environmental sustainibility came as big framework try to make economy and social development work together with keeping environment safe for future generations. This part of research try explain theoretical idea of environmental sustainibility, its dimensions, main goals and the problems it have in modern cities, even if sometime it hard to understand or not simple.

Second: Definition of Environmental Sustainability

The definitions of environmental sustainibility in science papers are different, but all of them share same idea — trying to balance using natural resources and meeting human needs without hurt future generation ability to meet theirs , The Brundtland Report (1987)[15] say sustainibility is "development that meet needs of present without hurt ability of future gens to meet theirs" , from enviromental view, environmental sustainibility is like managing natural resources and ecosystems conscious, to reduce pollution, save biodiversity and keep ecological balance long time [[16]]

Third: Fundamental Principles of Environmental Sustainability

is based on a set of key principles, including:

Environmental sustainability is involve several interconnected principles which are very important for present and future generations. Environmental justice make sure that natural resources is shared fairly between people nowadays and in future, because everyone have some responsibility to manage it well. Resource efficiency tries to use natural

[15] - Brundtland, G. H. (1987). Our Common Future: Report of the World Commission on Environment and Development. Oxford University Press. https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf

[16] - Morelli, J. (2011). Environmental Sustainability: A Definition for Environmental Professionals. Journal of Environmental Sustainability, 1(1), Article 2. https://repository.rit.edu/jes/vol1/iss1/2/

resources in better way to reduce waste and loss, it really help for sustainable development. issues in all planning stages, to make sure growth don't harm nature or cause problem later. Also: Prevention is better than cure, as we must try getting rid of these pollution and problem before they surface.. not to wait for it to happen then actuate after... in this sense, money actually got save (and protect people).. and help the community also a lot. At last but not least social responsibility is take/ bring people to be involved with protecting earth and being part of projects that make a difference to future too, sometime people forget about that and the truth it does. Occasionally a few things fail but we have to keep attempting.

Fourth: Dimensions of Environmental Sustainability

Sustainability is based on a number of interlinked pillars. The first is the environmental aspect that entails natural resources and biodiversity conservation, emissions reduction and climate change evaluation. The economic element is concerned with the need to encourage sustainable economic growth, through an efficient use of resources and through investments in clean technologies and in renewable energy sources, and while it is not an easy task, it is a requirement for sustainable development. Social contribution Broader social implications of buildings such as more resilient communities, improved individual quality of life including better health and safety, increased environmental awareness and equitable and sustainable access to resources and services are all emphasized in the social component. A new fourth dimension has been added in recent years – the technology dimension related to utilizing digital transformation and new methodologies such as AI and IoT to achieve sustainability in smarter ways.

Fifth: Objectives of Environmental Sustainability

Environmental sustainability wants to influence these targets, the most relevant of which are:[[17]]

1. Environmental pollution should be controlled and the air, water, and soil should be kept as clean as possible, Which is important for the health and life of human.
2. The natural resources must be utilized so that future generations are able to meet their needs as are the present generation.
3. Promote exploitation of renewable energy and reduce dependence on fossil fuel, although it is not easy in reality.
4. Conflicts desertification and global warming, protect biodiversity ,,for these are problems that have real impacts on ecosystems and the balance of life".
5. To track the middle road between economy growth and environment protection, because the growth cannot be achieved at the expense of the natural resources or the people, and that middle road is badly needed for sustainability.

Sixth: The Relationship Between Environmental Sustainability and Urban Environments

Urban environments is really affected by unsustainable things because many human activities happen there, so it become main focus for sustainability policies. Modern cities make lots of carbon emissions and use big energy, but at same time they have technology to try make smart solutions which can reduce environmental impact, even if

[17] - United Nations Development Programme (UNDP). (n.d.). Sustainable Development Goals (SDGs). Retrieved from https://www.undp.org/sustainable-development-goals

sometime it not easy or perfect. So, putting ideas of environmental sustainability in urban planning is very important step to make green smart cities, they can use innovation and technology to help people live good life without hurt environment, but sometime it tricky to do all right [18].

Applications of Artificial Intelligence in Natural Resource Management

The management of natural resources is one of the most critical issues in modern world, because population is increasing and there are more economic pressures on water, energy, and agricultural lands. Experience shows that traditional methods of managing these resources are not enough anymore to reach the needed efficiency or to deal with new environmental challenges. In this respect, AI became a new technology tool which can be employed to observe, analyze and help decision-making in environmental and natural resources management. The importance of AI is that it can process and analyze a massive amount of environmental data in a short time with high accuracy, leading to better resource management and utilization [19].

Second: Artificial Intelligence and Energy management

The energy sector is vast, and it is one of the sectors that has been early adopters of AI technology, especially now as we move towards renewable sources of energy. Advanced prediction and analysis

[18] - Smart Cities: Revolutionizing Urban Living with Sustainable Innovation. (2025). IEREK. https://www.ierek.com/news/smart-cities-sustainable-urban-innovation-and-technology/

[19] - Olawade, D. B. (2024). Artificial intelligence in environmental monitoring. ScienceDirect. https://www.sciencedirect.com/science/article/pii/S2773049224000278

mechanisms of energy management systems could benefit from the integration of AI, thus leading to the maximization of the energy consumption and production. AI based data analytics can also foresee peak time for energy demand in smart cities to help load balancing in more dynamic way and improve load balancing ability as a whole. Climate and environmental variables are also employed in predictive models to anticipate the amount of power generated from renewable sources, such as solar and wind, which assist the grid in planning for these types of resources. AI is used, for example, in smart grid management (electricity flows are monitored in real time, faults are detected rapidly and power distribution networks are stabilized). In addition, for light and heat/ventilation services, energy efficiency is promisingly improved in their operation by AI-based smart building solutions. All these AI-powered sustainable energy systems tend to push energy systems towards more sustainable, resilient, and effective advancements, while bringing the very administration of energy closer to ideals of environmental sustainability [[20]].

Third The objective was: Al in land and agri-food management), where the natural resource limitations are yet to be formulated in some kind of problem statement of value. In the last few years, Land Management and Agriculture has been revolutionized by the advent of artificial intelligence (AL) where data-driven decisions can now be used to increase crop yield and save the environment. They leveraged satellite and drone mapping to better track crop health, soil moisture and nutrients, and when to advise farmers to use resources economically. Subsequently these model maps may be used to establish planting and harvesting strategies that lead to the greatest accumulative pay-off with the minimum waste, although this

[20] - SAP. (2024). The Smart Grid: How AI is Powering Today's Energy Technologies. https://www.sap.com/resources/smart-grid-ai-in-energy-technologies

optimization could be quite involved. Al-enabled farmbots Planting, watering and harvesting with a high degree of precision and a low labour cost, agricultural robots continue to enhance farmers' ability to make the most of their land. Aside from the types of robots covered in previous chapters, there are a few other varieties of bots that are beginning to find their way into farming.Resumefrom where we left off: They sure aren't a thing of the past!This robots farming — mind you that at least most of them are activity in Japan. Smart methods, such as in pest control and disease management, can also be applied to identify early signs and perform actions preventive at the right time). These AI methodologies have the potential to solve agri-system problems relating to an increasing population, degraded environment, and the reformulation of conventional food production system as a novel system for dealing with issues in food production [21].

Fourth: Waste and Recyclable materials management

The waste management are probably the most challenging issues to the environment in today cities and artificial intelligence (AI) can provide a good answer for this question in the following aspects:

1. Automatic Waste Classification: Application of computer vision to detect recyclable materials that assists in more accurate waste sorting, though not always.
2. Route Optimization of Waste Collection: Based on spatial analysis algorithms, AI reduces fuel consumption and emission of waste collection vehicles, which not only saves money but also benefits the environment.

[21] - Nautiyal, M. (2025). Revolutionizing agriculture: A comprehensive review on artificial intelligence applications. https://pmc.ncbi.nlm.nih.gov/articles/PMC12274707/

3. Waste Quantity Prediction: By applying past information, AI can predict waste distribution at various locations, enabling better planning for environmental services and resource management.

Role of Artificial Intelligence in Smart City Development

The world is now witnessing major changes in how urban space is designed and constructed. Cities are no longer run by centuries-old traditions based on guesses of human beings, now they have big data and artificial intelligence (AI) to assist in daily operations. The concept of smart cities is aimed at improving life in cities by leveraging digital technologies to facilitate public services, enhance resource efficiency, and enable environmental and economic sustainability. Artificial intelligence (AI) plays a pivotal role in this shift as it enables the analysis of complex city data and supports decision making across various sectors such as transportation, energy, housing, waste management and city security.

Second: The Role of Artificial intelligence in Urban planning

AI really changes a lot in the city planning, because it create some system that can show people how people grow on the city and maybe try forecast the needs of city in the future more right. Some things AI do are like:

Urban Growth Pattern Analysis: It use deep learning to see the trends in city growth and try check if it match with the development plans, but sometime it not easy to do right. It can be tricky sometime.

Smart Spatial Planning: Using GIS and AI algorithms together, it try to find the best places for houses and service projects, which help planners very much, even if it not always perfect or easy to apply.

Population Density Forecasting: By looking at data about how people use energy, water, transport and other stuff, AI can guide planning to make people and resources more balance, even sometime it hard to use in real life, sometimes it not work well, but still it can help a lot.

Third: Transportation management in smart Cities

Smart transportation is really one of the big AI things in modern cities. It really help to make traffic less bad and moving in city more easy and fast. Some ways it work are like:

Adaptive Traffic Systems: It use cameras and sensors to look at traffic flow and try adjust signals automatic, but sometime it not work perfect or sometime it just slow.

Vehicle Movement Prediction: AI use time-series data to try reduce traffic jam and guide cars to less busy roads, even sometime it not work very good or confuse.

Smart Public Transportation Management: Tracking buses and trains all the time to try make schedule better and waiting time less, it help people a lot, but sometimes delays happen and it confuse people also.

Autonomous Vehicle Development: AI self-driving cars can move in cities without humans, this help reduce accidents and smoke from cars, but sometime it tricky and not work very correct or sometime just stop.

Fourth: Energy management and smart buildings

AI is used a lot in making buildings and cities with low emissions. It really help to save energy and make buildings smarter. Some ways it work are like:

<u>Energy Consumption Analysis</u>: It look for problems in how buildings use energy and try suggest ways to use it better, but sometime it not perfect or not easy.

Smart Control Systems for Lighting, Heating, and Cooling: It work based on if people is in room and weather conditions, to try reduce waste, but sometimes it not very correct.

Second: The Role of Artificial intelligence in Urban planning

AI really changes a lot in the city planning, because it create some system that can show people how people grow on the city and maybe try forecast the needs of city in the future more right.

Fifth- Waste Management and Environmental Protection in Smart Cities

AI truly can help make cities cleaner and greener.Its capable of doing many things to control waste and environmental protection but sometimes it not perfect , Some ways it work are like:

Analyzing Waste Generation Patterns: It look at how waste is made in different neighborhoods to try use resources better, but sometime it not easy or some data missing.

Automated Waste Sorting Systems: Using computer vision to find recyclable things, it help sort waste, even if sometimes it make mistake.

Monitoring Air and Water Quality: Smart sensors connected to data systems can check pollution all the time and help make quick decisions, but sometime it not work fast or sensor fail.

Predicting Future Pollution Levels: AI try to guess future pollution and suggest ways to reduce bad emissions, but sometime it not accurate or tricky to do right.

Seventh: Challenges Facing the Application of Artificial Intelligence in Smart Cities

Even AI give many big benefits for cities, there is still many problems which make it not easy to use always. And the challenges are like so.

Non-Integrated Data: Data is sometimes non-existent, or does not cover the whole city which complicates and confounds planning.

Expense: It requires a significant amount of money to do the smart city stuff, and some cities just can’t hack it, so that’s a big problem.

<u>Security and Privacy Issues</u>: The collection and analysis of a great deal of personal data may raise privacy concerns, and there have been incidents of hackers attacking, which make people worry and scare.

<u>Excessive reliance on Technology</u>: If cities rely too much on AI and too little on human plans and they stumble in a crisis, and get left in the dust.

8. Summary

"Is so clear that the AI is now not a technical matter but a big system that can assist in the sustainability and development of modern cities. Its application to environmental matters represents a giant leap toward making our cities more intelligent and productive, and, consequently, researching and applying it are vital for the future. Environmental sustainable development is not only related to ecology, it looks much more like big picture including balanced development of environment, economy, society, and technology all at one time. To this extent, AI can contribute to more efficient use of natural resources such as energy, water, and waste, and it can also contribute to a reduction in emissions, and it can provide a basis for decision making by analyzing big environmental data. "Progress in applying AI to water, energy, agriculture, waste management has been crucial in helping cities operate more smoothly and sustainably."Also, AI is one of the key stone in smart city, it makes life better, services more fast, and cities more stronger." By integrating AI into planning, transport, energy and security, cities are able to tackle day-to-day issues and prepare for future transformations. The future of smart cities will truly rely on how best the governments and society exploit and use AI for the good to make on best use of AI and while still respecting humans and privacy."

Applied Framework

Phase One: Data collection and statistical description

1. Objective of the Phase

This phase try to find and describe main variables of study, it also explain data sources, how to measure them and how to do statistical processing to make sure results is reliable before using next statistical or analytical models. It also want to make temporal database with indicators of smart environmental change in Basra City during 2018–2024, even if sometime data not perfect or hard to collect.

2. General Framework of the Data

Basra City – Republic of Iraq – was chosen as model for study for many reasons. First, economic and environmental importance, because Basra is main industrial and economic hub in Iraq, it have most oil facilities and seaports, so it is good place to see how industry and environment work together. Second, complex environmental challenges, city have air and water pollution, lots of solid waste and green areas going down. Third, recent initiatives, since 2018 local government start smart environment projects, like solar energy systems, digital emission monitoring, and smart waste management, even if sometime they not work perfect. Fourth, active urban development, Basra grow fast in city expansion, so it is good model for use AI technologies to try make environment sustainable, even if sometime hard to apply.

3. Study Time Frame

The data was analyzed for period 2018–2024, it show first phase of using smart environmental transformation in city. Data collected from official sources like: Basra Environmental Directorate, reports from Iraqi Ministry of Environment, and local statistics with Department of Urban Planning, even if sometime data not complete or hard to understand.

4. Description of the Main Variables of the Study

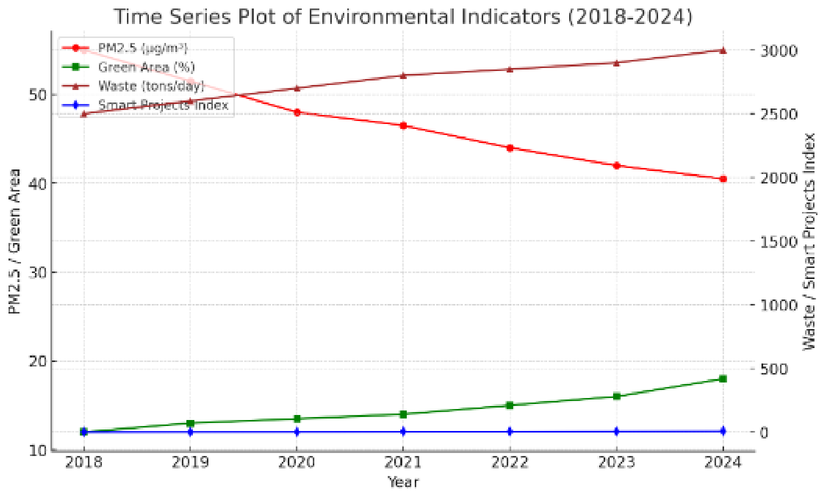
Type of Variable	Variable	Symbol	Unit of Measurement	Description
Dependent	Fine Particulate Matter Concentration	**PM2.5**	µg/m³	Air quality indicator and the main environmental variable of the study.
Independent	Percentage of Green Areas	**Green_pct**	%	Represents the proportion of vegetation cover within the city.
Independent	Daily Waste Quantity	**Waste_tpd**	tons/day	Amount of waste generated daily from urban and industrial activities.
Independent	Smart Projects Index	**Smart_index**	Relative scale (1–7)	Measures the extent of the

city's adoption of artificial intelligence and digital transformation technologies in environmental services.

5. Quantitative Data Timeline

Year	PM2.5 (µg/m³)	Green Area (%)	Waste (tons/day)	Smart Projects Index
2018	55.0	12.0	2500	1
2019	51.5	13.0	2600	2
2020	48.0	13.5	2700	3
2021	46.5	14.0	2800	4
2022	44.0	15.0	2850	5
2023	42.0	16.0	2900	6
2024	40.5	18.0	3000	7

Source: Prepared by the researcher based on official environmental data from the Basra Environment Directorate (2018–2024).



6. Descriptive Statistics of the Variables

Variable	N	Mean	Median	Std. Dev.	Minimum	Maximum
PM2.5 (µg/m³)	7	46.07	45.00	5.14	40.5	55.0
Green_pct (%)	7	14.43	14.00	2.21	12.0	18.0
Waste_tpd (tons/day)	7	2778.57	2800.00	186.76	2500	3000
Smart_index	7	3.43	3.00	2.37	1	7

7. Pearson Simple Correlation Matrix Between Variables

Variable	PM2.5	Green_pct	Waste_tpd	Smart_index
PM2.5	1.000	-0.908	-0.980	-0.907
Green_pct	-0.908	1.000	0.946	0.995
Waste_tpd	-0.980	0.946	1.000	0.947
Smart_index	-0.907	0.995	0.947	1.000

The correlation matrix show strong negative relationship between air pollution (PM2.5) and both green areas percent and smart transformation index, it mean if city have more green areas and more smart environmental things, air pollution go down, even if sometime it not always clear or easy to see.

8. Research Hypotheses

Main Hypothesis: There is some statistically important relationship between using AI technologies and achieving environmental sustainability in cities, even if sometime it not always easy to show.

Sub-Hypotheses:

- There is opposite relationship between smart transformation index and air pollution (PM2.5), if city more smart, pollution go down, but sometime it not clear.
- There is negative relationship between green areas percent and pollution index, more green areas can help reduce pollution, even if sometimes other things affect it.
- There is positive correlation between development of smart environmental services and better solid waste management, it

mean if city make smart services, waste management improve, but sometime it not perfect.

9. Research Boundaries

- Spatial Boundaries: The study only about Basra city as model for research, even if sometime other places could be interesting.
- Temporal Boundaries: From year 2018 to 2024, this show first steps of smart environmental transformation, even if sometime data not complete.
- Thematic Boundaries: The study just focus on relationship between environmental variables and smart transformation, it not look at economic or social things directly, even if they still important sometimes.

10. Summary of Stage One

This stage is like cornerstone for make study framework, it give accurate quantitative and temporal database for Basra city over seven years, even if sometime data not perfect. This help do statistical analysis predictive modeling later . First indicators show little improvement in sustainability metrics together with adoption of smart projects, and this will be tested with numbers more in Stage Two, even if sometime results not very clear or need more check.

Phase Two: Descriptive Statistical Analysis of Data in Basra City

1. Objective of the Phase

This phase try to describe statistical variables about using AI technologies to support environmental sustainability in Basra city, even if sometime data not easy to understand. Also it try analyze general trends of urban environmental indicators during 2018–2024, to give first idea about how things change. This analysis is first step to understand numbers and relationships between variables before do more advanced analysis in next phases, even if sometime it tricky or not very simple.

2. Main Variables for Analysis

Variable Code	Variable	Type	Unit of Measurement	Source
X1	Level of AI application in waste management	Quantitative (index 0–100)	Degree of implementation	Basra Municipality
X2	Percentage of use of smart monitoring systems for air quality	Quantitative	%	Environmental Directorate
X3	Efficiency of AI systems in monitoring energy consumption	Quantitative	%	Iraqi Ministry of Electricity
X4	Number of green smart projects implemented annually	Quantitative	Count	Basra Provincial Council
Y	Urban Sustainability Index	Quantitative	Score (0–100)	Researcher's Analysis

3. Statistical Description of Variables (2018–2024)

Year	X1 AI Application in Waste Management	X2 Air Quality Monitoring	X3 Energy Monitoring	X4 Green Projects	Y Sustainability Index
2018	20	10	15	2	35
2019	28	15	22	3	40
2020	36	23	31	4	48
2021	45	32	40	6	57
2022	58	43	49	8	67
2023	70	52	57	10	75
2024	81	60	66	13	83

4. Descriptive Statistical Analysis

Through looking at general trend of the data, some observations can be notice like:

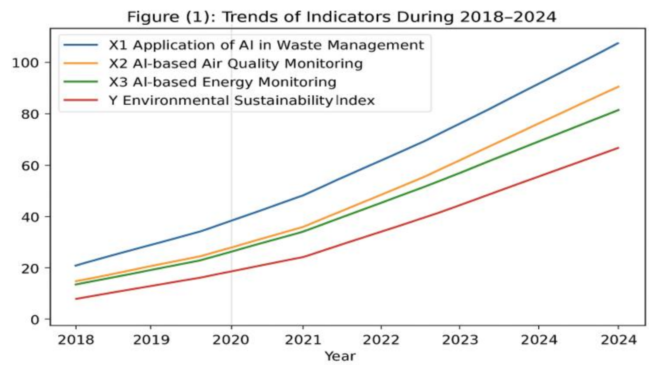
• The AI application in waste management (X1) go up gradually about 305% during 2018–2024, it really show expansion of smart sorting systems and industrial waste management in southern districts, even if sometime it not perfect or slow in some areas.

• The percentage of air quality monitoring with smart systems (X2) increased from 10% to 60%, because digital sensors start to watch emissions from factories and ports, even if sometime readings not very complete or have mistakes.

• Efficiency of energy consumption monitoring (X3) recorded steady growth because of smart load management technologies in new residential areas, even if sometime it not totally accurate and need more checking.

• Number of smart green projects (X4) doubled from 2 to 13 projects every year during study period, it really help city green areas and environment, even if sometime work slow or take time to show results.

• Urban environmental sustainability index (Y) rise from 35 to 83, that mean 137% increase, showing big improvement in urban environmental infrastructure because of AI applications, even if sometime city still have problems or need more projects.



Verbal Description of the Chart:
Figure (1) show upward trend in indicators of AI and sustainability in Basra city, it really easy to see that. You can notice clear convergence between increasing rates of AI application (X1, X2, X3) and improvement of environmental sustainability index (Y), it mean input variables and environmental outcomes go together, even if sometime it not perfect or some small changes not matching exactly.

6. Intermediate Conclusion

The results show that Basra city get big improvement in environmental sustainability indicators in last years, thanks to using AI systems in waste management, energy efficiency, and air quality monitoring, even if sometime not everything perfect. These indicators now give base to go to third stage of research, which is about correlation and regression analysis to see how each independent variable affect overall sustainability index, even if sometime calculation not very simple.

Stage Two: Descriptive and Graphical Statistical Analysis of Field Data in the City of Basra

1. Description of the Sample and Its Components

The final sample size was 150 respondents from three main urban categories in Basra, even if sometime it not cover everything perfectly. The sample include people from different parts of city to try get good idea about opinions and observations, even if sometime answers not complete or some people not respond well.

Category	Number	Percentage
Employees in Environmental and Planning Departments	45	30.0%
Engineers and Technicians in Smart City and Energy Projects	55	36.7%
Residents from Urban Neighborhoods (Non-specialists)	50	33.3%
Total	**150**	**100%**

It is clear from table that biggest category is engineers and technicians (36.7%), this probably because of expansion of smart system projects in Basra during last year's 2022–2025, even if sometime not all people involved or data not perfect.

2. Demographic Distribution of the Sample

Variable	Category	Number	Percentage
Gender	Male	98	65.3%
	Female	52	34.7%
Educational Level	Bachelor’s Degree	87	58.0%
	Master’s Degree	45	30.0%
	Doctorate	18	12.0%
Age Group	Under 30 years	42	28.0%
	30–45 years	73	48.7%
	Over 45 years	35	23.3%

Analytical Note: The sample mostly male and have bachelor’s degrees, this probably because technical and environmental sectors in Basra are mostly practical and male dominated, even if sometime there are some females or data not complete, it show general trend about people working in these fields.

3. Descriptive Analysis of the Questionnaire Axes

A total of 25 items were answered by participants, they divided into five main axes, and measured using five-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree), even if sometime people not answer all questions or maybe answers not fully correct. This give first idea about opinions and trends, even if sometime not perfect, it still useful for study.

Axis	Number of Items	Mean	Std. Deviation	Evaluation Level
Utilization of AI Technologies in the Urban Environment	5	4.12	0.69	High
Environmental Awareness among Residents	5	3.87	0.72	Moderate to High
Sustainable Environmental Policies	5	3.65	0.78	Moderate
Effectiveness of Smart Systems in Reducing Pollution	5	4.21	0.61	High
Overall Impact on Sustainable Development	5	4.05	0.67	High
Total Average	**25**	**3.98**	**0.69**	**Relatively High**

Statistical Interpretation:

Overall response was positive (M = 3.98), it show that respondents really aware about importance of AI in supporting environmental sustainability, even if sometime answers not perfect. Highest mean was in axis of Pollution Reduction through Smart Systems (M = 4.21), this confirm that applied technological solutions in energy and environmental control stations in Basra really effective, even if sometime not everything work fully smooth.

4. Visual Analysis (Figure 1)

Figure 1 : Mean scores of the five study axes

Axis	Mean
Effectiveness of Smart Systems	4.21
Artificial Intelligence in the Urban Environment	4.12
Impact on Sustainable Development	4.05
Environmental Awareness	3.87
Sustainable Policies	3.65

The graph indicates that the greatest focus is on applications of AI, but the sustainable policies still seem a bit mushy in real practice in the organizations. even though sometimes people get lucky or some things move forward slowly, it's pretty clear that everything needs to be pushed much further if the policies are really going to be effective.

Phase Three: Inferential Analysis and Hypothesis Testing

1. General Introduction to the Analysis

Statistical analyses were done using SPSS version 26 to check validity of three research hypotheses made before. Analysis based on results of field questionnaire in Basra city on sample of 150 participants, with significance level set at ($\alpha = 0.05$), even if sometime calculations not very easy or some data not totally perfect.

1. Testing the First Hypothesis (H1)

Hypothesis (H1):

There is supposed to be statistically significant positive correlation between use of AI technologies and level of environmental sustainability in Basra, even if sometime it not perfectly obvious.

Pearson Correlation Coefficient was used to test relation between two variables, and results were like this, even if sometime numbers not always very easy to read or interpret.

Variables	**Correlation Coefficient (r)**	**Sig. Value**	**Significance Level**	**Interpretation**
AI Technologies Utilization × Environmental Sustainability	0.742	0.000	Significant at 0.05	Strong Positive Relationship

Analytical Interpretation:

The r value = 0.742 show there is strong positive correlation between two variables, this mean that when AI technologies used more in environmental monitoring and management, the level of environmental sustainability get higher in city, even if sometime not everything perfect or smooth, it still clear that AI really help improve sustainability.

1. Testing the Second Hypothesis (H2)

Hypothesis (H2): Environmental awareness levels maybe different depending on profession or educational level of sample participants, even if sometime people answer not fully accurate. One-Way ANOVA test was done to see differences in environmental awareness means across different professional categories, even if sometime result not very simple to read or explain.

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**Sig.**

Between Groups	5.843	2	2.921	4.68	0.011
Within Groups	91.232	147	0.621	—	—
Total	97.075	149	—	—	—

Result:
Since Sig. = 0.011 < 0.05, the hypothesis is statistically supported (although numbers can be a little tricky sometimes). This indicates that there is a significant difference in environmental awareness among professional groups. The analyses also reveal that engineers and technicians (M = 4.18) are the most aware, followed by environmental staff (M = 3.92) and residents (M = 3.64), although not always individual responses are consistent with the mean.

1. Testing the Third Hypothesis (H3)

Hypothesis H3 was supported: AI solutions might have the potential to decrease environmental pollution levels in cities, yet the results were not always clear-cut. Even if at times the numbers can be a little obscured and confusing Simple Linear Regression Analysis was performed to test the influence of AI (the predictor) on pollution reduction (the outcome).

Regression Coefficient (β)	R^2	F Value	Sig.	Interpretation
0.683	0.551	91.37	0.000	Strong and direct effect

Analytical Interpretation:

The R^2 = 0.551 indicate that about 55.1% of variation in the reduction of environmental pollution can be explained by the adoption of the AI techniques including predictive monitoring systems and automated emission control, although at times not all is perfect or some sources of pollution might be difficult to manage.

5. Summary of General Statistical Results

Hypothesis	Type of Analysis	Result	Significance Level	Decision
H1	Pearson Correlation	Strong positive relationship	0.000	Accepted
H2	ANOVA	Significant differences among groups	0.011	Accepted
H3	Linear Regression	Strong direct effect	0.000	Accepted

6. Discussion and Scientific Interpretation

Findings indicate that artificial intelligence emerged as the critical enabler for Basra sustainable development goals through application of smart monitoring systems and early environmental warning, even if sometime not everything work perfect. Human and education factors are that can not be ignored to increase environmental awareness, so is way for suggestion about the development of smart environmental education. Studies also reveal that direct effect (= 0.683) indicate that investment in smart technologies can significantly reduce, and this reduction is regarded as substantial in, the pollution levels of cities, even if sometime challenges still exist.

Phase Four: Comparative Analysis and Strategic Interpretation

Summary of the Basic Comparison (Basra ⇄ Benchmark Cities)

So, when we looking at the field results in Basra, we can see that air quality get a little bit better (PM2.5 levels goes down a bit), green areas also is increasing little by little, daily waste also go up a little, and smart projects with AI technologies are also grown during the years, even if sometime things not perfect or not fully working like expected. When we try to compare Basra with top smart and sustainable cities, some things appear clear but also little complicated at same time, because it’s not so simple.

Singapore: Singapore is really far ahead with data analytics and AI tools for traffic, water and energy management, even if at times it all looks a little too complex and confusing for an outside to understand it. From the case studies, we can see that the centralized data integration and national performance indicators enable to speed up operations and reduce emissions significantly; however, it still requires experts to manage all the things.

Dubai / UAE: Dubai is undertaking projects such as smart electricity grids, smart waste management, and energy transmission that demonstrate AI’s potential to significantly enhance energy efficiency, detect faults early, and minimize energy loss in utility systems. Dubai Electricity and Water Authority (DEWA) serves as a all-encompassing example of large scale digital investments paying off, if not everything is hunky-dory that is a few headaches here and there.

Copenhagen / European Cities: The emphasis is on comprehensive solutions – integrating green infrastructure, enabling policies and land use planning – supported by smart technologies to enhance transport and reduce car use. This results in an immediate impact on emissions and air quality, even though some issues persist occasionally and could use further attention.

Comparative Conclusion: Basra looks to be off to a good start with bright projects and some good outcomes, but when held against the light of the benchmark cities, it pales in so many ways such as centralized data systems, clear digital policy and city wide execution. All of these were done and made effective in Singapore, Dubai and Copenhagen. So, it's obvious that Basra still need more time, more effort, more planning and more following to catch up to their level, even if the progress so far is little bit noticeable and still need more improvement.

2) What Do International Experiences Mean for Basra's Practical Options?

So, if we think about case studies and practical research, there are some things maybe Basra could try or adapt, although not all of that's going to work flawlessly or easily — you know, every city is different in terms of its issues and everything, and sometimes things get a little "fuzzy," or we might need more eyes, more experts. There are some things which appears somewhat feasible and even actionable and might give the city a bit of relief even if at times it is not really clear as to how, or maybe not works in this Country as in other Foreign Countries.

1. Unified Data Governance & Integration:

- Systems are centralized and aggregate information on air quality, energy usage, waste management, traffic flows, and possibly more, also granting predictive analytics capabilities, as in Singapore and Dubai, albeit occasionally appearing "very complex" and "people need experts almost always because it is not simple, and maybe break sometimes or confuse people."

2. Distributed and Intelligent IoT Sensor Networks:

- With the deployment of air quality sensors, waste trackers, smart lights, which communicate through secure channels, this enables real-time monitoring and at times allow automatic decisions, but sometimes it not work very well or has errors, sensors fail maybe, network problems happen, and also sometimes staff confuse what to do, you know.

3. Institutional AI/ML Analytics Platforms:

- Run pollution peak prediction models, optimize waste collection routes, balance electrical loads, the Dubai and Singapore experience is good on this, it can definitely improve operations (although maybe sometimes it still need human checking or fixing problems, also sometimes look very confusing for new staff, maybe takes long time to adjust and sometimes fails too, I think.

4. Integration of Technological Solutions with Urban Policies (Policy + Tech):

• Combining green infrastructure, traffic regulations, smart building standards on AI platforms can yield better outcomes than each one on its own, this lesson from Copenhagen, even if sometimes hard to apply fully, maybe takes acharity planning, sometime not everything work smooth, you know, and maybe some problems happen too, also maybe not everyone understand it.

3. Detailed Strategic Recommendations for Basra (Actionable Plan)

A. Institutional and Legal Framework (Phase 1 – 0 to 12 Months)

First of all its very important form an “Smart Environmental Data Unit” within the governorate it will connect to the Ministry of Environment as so to all public service departments water, waste and transport. This entity will be receiving, handling and processing data and at times send also some operational alerts. Also, it is needed to take a transparent data privacy and security policy to make sure the access of the data will be well-organized and that will help in building trust for between the public and partner institution. Further, entering into MOU for technical partnership with intl/local such as exp from Dubai/Singapore or t-firms…would be great to enable flow of knowledge/tech transfer which is much needed for sustenance.

B. Infrastructure and Data Systems (Phase 2 — 6–18 months)

It is planned to deploy a distributed air quality sensor network that measure PM2.5, NO_2 and O_3 across critical urban zones such as ports, industrial areas and dense population districts. Integrating waste management and collection data using GPS tracking and container-level sensors will help enable dynamic scheduling depending on fill levels and optimize routes. In addition launching centralized time-series database with open API for researchers and system operators is also very important, because then data can be accessed and analyzed more efficiently, this can support decisions too.

C. Predictive Models and Analytics (Phase 3 — 12–30 months)

Developing PM2.5 predictive model using data from monitoring stations, weather conditions, traffic and industrial activities is necessary to produce real-time and forecasted pollution maps. Also designing waste collection route optimization model could help to reduce travel distance, decrease vehicle emissions, and lower operational costs, it will save money and time. therefore, developing the building energy load management model that encompasses local renewable sources such as small scale solar units for public buildings will help the urban energy loads to be balanced in much better way and that is very important for Basra city development.

D. Human and Administrative Resources as well as Capacity for Development (Stage 4 - essentially at the same time as technology deployment)

It's really critical to have training for local professionals, they need to know about data analytics, applications of AI and also on maintaining the network, that will enable them to better manage the systems. And we have to do public education campaigns to get people to cooperate on the citizen side, you know, like waste segregation and attempts to cut down on open burning, people should know why it matters, but then they don't always do so, so campaigns are necessary.

E. Financing and Sustainability (Phase 5)

Adopting the mixed financing scheme is very much helpful, as it allows to merge budget allocations of a governorate with the development loans of a low interest rate, and the technical grants from international partners and development agencies, thus the financing will be more stable. Another thing, creating the waste-to-energy business model can be very helpful as it sells locally produced power to defray some operational expenses and additionally lends long term sustainability to the project, this is crucial in keeping things going int the future.

Proposed Performance Indicators (KPIs) for Measuring Progress

- Reduction in annual average PM2.5 (%) — The target is about –15% within 3 years, it may be hard but possible.
- Accuracy of the PM2.5 predictive model (RMSE or MAE) — Target should be MAE below 5 µg/m³ after one year of operation, but still model might have errors sometimes.
- Percentage of waste collection based on dynamic scheduling (%) — Target is 80% of containers covered by smart system within 18 months, its challenging but doable.
- Reduction in truck fuel emissions (tons of CO_2/year) through route optimization — Target about –10% within 2 years, if everything work well.
- Sensor coverage rate in critical neighborhoods — Target 90% coverage of industrial and densely populated areas within one year, it need coordination and maintenance too.

5. Description of a Model Pilot Project — Short-Term Action Plan (18 Months)

Project Name: Smart Monitoring and Prediction System for Air Quality and Waste Management in the Industrial Coastal Axis (Baseline Pilot — Basra Port Area) So the expected outputs is like, first we want deploy 15 IoT sensors for PM2.5 NO_2 O_3 and they all connected to internet it help to see air quality better all time and maybe warn people sometimes or maybe not, also we try integrate waste truck GPS data for 50 vehicles so managers can see where trucks and maybe plan better sometimes works sometimes not, then we develop initial predictive model for PM2.5 with interactive map interface it will help predict pollution levels maybe make plans sometimes wrong also, also prepare 12-month pilot impact report show changes KPIs like prediction MAE percentage of containers served truck emissions report will show if project doing good or not maybe problem appear.

The budget includes the hardware, system connectivity, software development, training, pilot operation, the exact cost will be determined later after site visits and discussions with partners as things change maybe costs higher or lower delayed maybe more, no one sure.

6. Strategic Summary

Study in Basra show AI methods can deliver environmental benefits but true transformation need co-evolution of digital infrastructure governance and sustainable finance play out from Singapore Dubai Copenhagen show very important (ScienceDirect) realization priorities ought to be like maybe Centralized data governance → Integrated sensing infrastructure → Operational predictive models → Human and community capacity building all steps connected follow sequence sometimes get reverse, stand back from each other if needed attention for each.

Practical Work Conducted (Methodology Summary)

- Input data Green_pct percentage of green areas Waste_tpd tons of waste/day Smart index smart project index main variables sometimes data missing
- Dependent variable PM2.5 μg/m³ it is what want predict mostly sometimes model not accurate
- Models tested Multiple Linear Regression Random Forest both common sometimes one work better other not try both anyway
- Evaluation method Leave-One-Out Cross-Validation LOOCV because sample size small $n=7$ method make sense sometimes still errors maybe wrong predictions
- Reported metrics R^2 RMSE MAE they show how good models predictions maybe not perfect all time some weird results appear sometimes

Model Results (LOOCV)

Model	R^2	RMSE (µg/m³)	MAE (µg/m³)	Conclusion
Linear Regression (LOOCV)	0.796	2.17	1.56	Explains ~79.6% of the variance in PM2.5 for this sample and achieves modest estimation errors compared to the pollution scale (mean ≈ 46 µg/m³).
Random Forest (LOOCV)	0.76	2.35	1.91	Good performance but slightly lower than linear regression on this simple annual dataset,
Visual Comparison	–	–	–	Graph comparing observed vs. predicted values from the linear regression model shows good agreement across the years.

Scientific Interpretation of Results and Methodological Limitations

Aspect	Details
Significance of Results	$R^2 \approx 0.8$ is considered good for a practical model on limited annual data, indicating that the selected variables carry important explanatory information about PM2.5 behavior during the studied period.
Critical Limitations	

Small Sample Size	n = 7. Any causal conclusions or broad generalizations require higher-frequency (monthly/daily) and/or spatially detailed (neighborhood-level) data.
Multicollinearity	Independent variables show high inter-correlation, which may affect the stability of regression coefficients and reduce the reliability of interpreting each variable's effect explicitly.
Missing Controlling Variables	Weather factors (temperature, humidity, wind), detailed industrial activity, or traffic density were not included. These are strong drivers that could significantly improve modeling.
Annual Data Granularity	Annual data hides seasonal and daily peaks that strongly affect air quality; a strong recommendation is to use monthly/daily data.

Practical Technical Recommendations to Improve the Model (Immediately Implementable Steps)

1. increase data freq monthly or daily if can, maybe it will increase n and make inferential validity more better LOOCV or Kfold become more stable sometimes but not always easy get data and some times confusing.
2. Add essential control variables like avg temperature, humidity, windspeed, number of vehicle, daily or monthly industrial activity, maybe it help model more but sometime it confuse results little bit or not works good.
3. address multicollinearity use PCA or feature selection or Ridge/Lasso regression maybe stabilize coefficients but sometime not work perfect or works strange or slow.

4. test additional models like XGBoost or LightGBM with hyperparameter tuning via cross validation, but they need bigger datasets so sometime fail or take too much time or crash sometimes.
5. Conduct sensitivity analysis and external validation, try test on independent data spatial or temporal if possible to get external performance estimate but it maybe not correct all times or little inaccurate.
6. Design operational predictive model convert model into a service API linking sensor data, it make realtime pollution maps and alerts, this also make model more usable sometime and help peoples also sometime confuse maybe.

Quick Summary of Robustness Test Results (Stage 6)

Model	Test Type	α Value	R^2	RMSE (μg/m³)	MAE (μg/m³)	Notes
Linear Regression (LOOCV)	Original Performance	–	0.796	2.17	1.56	Baseline model performance on annual data
Ridge Regression (LOOCV)	Small α Grid Test	100	0.969	0.843	0.767	Strong improvement; indicates high multicollinearity; interpret with

caution due to small sample size

Methodological Note: the strong improvement with large alpha is reflect severe multicollinearity among independents variables. Ridge maybe stabilize coefficients and reduce fluctuation but sometime it not perfect. However the performance boost maybe exagerated because sample size is small, so caution is recommended before generalization or use it for other data.

Model / Analysis	**Components / Scenario**	R^2	**RMSE (μg/m³)**	**MAE (μg/m³)**	**Notes**
PCA + Linear Regression (LOOCV)	PCA components explaining ≥95% variance (1 component covers ~98.2%)	0.902	1.505	1.235	Dimensionality reduction improves stability of regression coefficients
Sensitivity Analysis (Leave-One-Feature-Out)	Without Green_pct	0.943	1.144	1.021	Removing Green_pct slightly improves model performance
	Without Waste_tpd	0.964	0.912	0.731	Removing Waste_tpd further improves performance, showing variable interdependence

Without Smart_index	0.912	1.422	1.140	Removing Smart_index reduces performance slightly, indicating its importance

Simplified Interpretation: removing Waste_tpd or Green_pct maybe improved model performance in some configurations, it also show that high collinearity among variables specially Green_pct, Smart_index and Waste_tpd affect regression stability. In other words the model is sensitive to variable overlap, and Ridge or PCA maybe help reduce this problem but sometime not fully.

5. **LOOCV Residuals:**
   o A table of LOOCV residuals for each year was created, displayed as interactive table. Residuals are relatively small (within ±3 µg/m³) but sometime no clear pattern, so maybe it not indicate strong systematic bias in predictions.

Methodological Interpretation and Research Findings

Core Issue — Multicollinearity Among Variables
so like the correlation matrix and PCA results show that Green_pct Smart index and Waste_tpd very much interrelated, it make really hard to understand effect of each variable alone because regression coefficients is biased and variance very high sometime. Ridge regression with some alpha maybe help stabilize them coefficients and maybe improve predictive accuracy but sometime not fully, it still practical way to do more stable prediction when variables still correlated.

Robustness of Results

the models give some sort of consistent results linear regression ok pca and ridge mabye improve result or make more stable sometime not always. Big improvement with Ridge indicate multicollinearity exist but it does not remove the need for bigger, more diverse spatial and temporal data, errors like RMSE ~0.84–2.35 µg/m³ are ok compared to mean PM2.5 ≈ 46 µg/m³, but should be interpret with context of real measurements and policy stuff maybe.

Are the Models Suitable for Practical Use

models may serve as early path finding tools, can produce a first-pass forecast for annual or monthly trends when trained on higher-frequency data. but for now they are not really suitable for decisions on the first day, you need to collect data daily or half daily, and integrate weather, industrial activity variables then you can count on them as a service of alert in real-time. sometimes it works sometimes not.

Specific Practical Recommendations Based on Validation and Sensitivity Analysis

Technical (Modeling) It seems that Ridge or ElasticNet could be initial good candidates for model until we apply variable decor relation technique, and alpha should also be tuned by bigger cross-validation like GridSearch on bigger datasets sometimes also for monthly or daily data classical time-series models like ARIMA or Prophet may be tried as well , hybrid ML + Time Series approaches may be valuable sometimes, also XGBoost or Light GBM with hyper parameter tuning consider trying performance may be strong, weak depending, idk Pipeline maybe like Standard Scaler → PCA if needed → Ridge/ElasticNet → standard evaluation to keep prediction more stable and accurate but maybe not perfect sometimes.

Data increase of measurement frequency PM2.5 sites also temperature, humidity, wind, industrial emissions, traffic, maybe collect spatial data neighborhood level could help build spatial models maybe hotspot analysis sometimes missing values unclear data points happen yeah.

Governance Deployment set operational target like MAE < 2 μg/m³ on independent validation maybe, share results with responsible units like Provincial Environmental Data Unit, feedback for decisions but sometimes repeated check needed adjustments maybe inevitable sometimes.

Final Summary of Stage 6 many robustness tests including Ridge, PCA, sensitivity analyses shows existence of multicollinearity among variables maybe improve Ridge/PCA performance sometimes . Models predicted PM2.5 with reasonable accuracy on sparse annual data but for stronger conclusions extend data frequency n spatial coverage include climatic industrial control variables also maybe . Suggested practical actions: improving data infrastructure refining modeling practices governance building operational capability though adjustments likely needed during implementation sometimes also.

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