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 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
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

[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
[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

(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

Fifth research objectives

this research aim to achieve the following objectives

1- to analyze the role of artificial intelligence in achieve environmental sustainability in modern cities?

2- to identify the most important practical applications of AI in various environmental fields?

3- to study the technical and administrative challenges facing the employement of AI in urban Environments?

4- to propose a strategic model for integrate AI with sustainable development plans in Smart cities?

Sixth research hypotheses

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?

3. the integration between artificial intelligence and environmental policies can lead to improvement in the quality of life in urban environments?

7. 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

[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

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

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”.

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

[5] - National Geographic Education. (2024, October 30). Urban area. National Geographic. https://education.nationalgeographic.org/resource/urban-area/
[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
[9] - Turing, A. M. (1950). Computing machinery and intelligence. Mind, 59(236), 433–460. https://doi.org/10.1093/mind/LIX.236.433

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

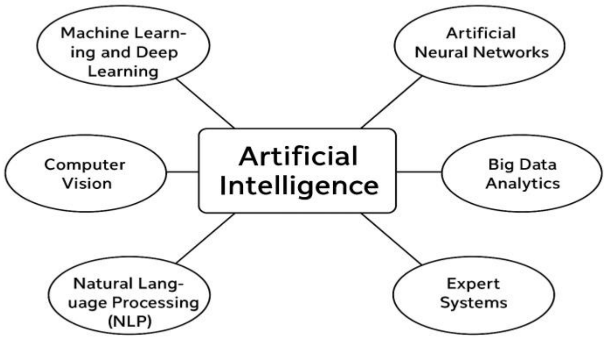
[11] - Rumelhart, D. E., Hinton, G. E., & Williams, R. J. (1986). Learning representations by back-propagating errors. Nature, 323(6088), 533–536. https://doi.org/10.1038/323533a0

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

[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 sustainability 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 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.

[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/

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 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]].

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

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

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 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 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

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

[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

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.
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.

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

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:

Energy Consumption Analysis: 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.

Security and Privacy Issues: 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.

Excessive reliance on Technology: 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.

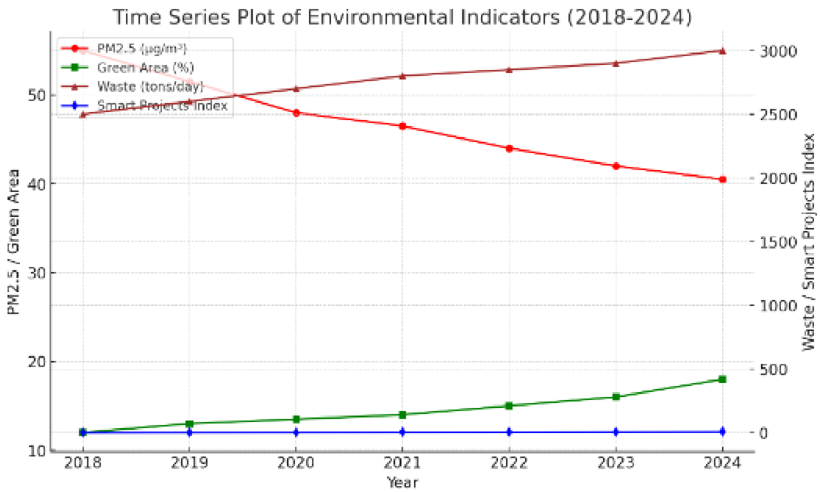
4. Description of the Main Variables of the Study

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	Quantitative	%	Environmental Directorate

	quality			
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.

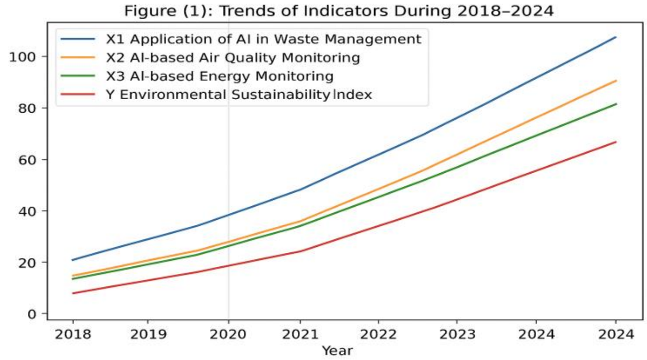
• The percentage of air quality monitoring with smart systems (X2) increased from 10% to 60%, because digital sensors start to watch emissions from factories and ports, even if sometime readings not very complete or have mistakes.

• 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.

Figure (1): Trends of Indicators During 2018–2024



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 (α = 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, likely due to small sample size and tree-based models' sensitivity to low n.
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	Small α Grid	100	0.969	0.843	0.767	Strong improvement;

Regression (LOOCV)	Test					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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