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Science and Technology for Sustainable Future
Volume I

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PREFACE

The dawn of the 21st century has heralded unprecedented advancements in science and technology, reshaping every aspect of human life. From communication and healthcare to agriculture and energy, scientific innovations are propelling society forward at an astonishing pace. Yet, amid this rapid progress lies an urgent and overarching challenge—the need for sustainability. As the global population grows and natural resources dwindle, the imperative to develop sustainable solutions through science and technology has never been more critical.

This book, Science and Technology for Sustainable Future, is a comprehensive collection of insights, research findings, and innovative approaches aimed at promoting sustainable development across diverse sectors. It brings together the work of scholars, researchers, and professionals who share a common vision: to harness the power of science and technology for the well-being of current and future generations.

The chapters in this volume explore a wide array of themes, including renewable energy technologies, sustainable agriculture, environmental conservation, green chemistry, climate change mitigation, and smart infrastructure. By highlighting both theoretical advancements and practical implementations, this book seeks to bridge the gap between research and real-world application, inspiring new solutions to pressing global challenges.

Our objective in compiling this volume is not only to share knowledge but also to stimulate dialogue, collaboration, and action among academicians, policymakers, industry leaders, and students. It is our hope that this book will serve as a valuable resource and a catalyst for innovation in building a more equitable, resilient, and sustainable world.

We extend our sincere gratitude to all the contributors for their scholarly work and to the editorial team for their dedication and commitment to this project. Together, we embark on a journey toward a sustainable future—guided by science, driven by innovation, and grounded in a deep responsibility to our planet and its people.

- Editors

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SUSTAINABLE ENERGY AND THE CIRCULAR ECONOMY: TRADITIONAL KNOWLEDGE, CONTEMPORARY INNOVATION

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1. Introduction:

Environmental deterioration, resource depletion, and climate change have made sustainability a major topic in science and technology. Even if contemporary technologies like wind turbines and solar panels are the talk of the town, ancient societies also followed sustainable practices, frequently out of need. This chapter examines how ideas of renewable energy and the circular economy have changed from antiquity to modern high-tech solutions, making links between conventional wisdom and contemporary advancements to support the idea that sustainability will be ingrained in both tradition and state-of-the-art research in the future.

2. Ancient Foundations of Sustainable Practices

2.1 Renewable Energy in Ancient Civilizations

- Solar architecture was used by the ancient Egyptians to control light and heat in their houses and temples (Butti & Perlin, 1980).
- Vertical axis windmills were used in Persia (c. 500–900 AD) to pump water and grind grain (Needham, 1965).
- In ancient Greece and China, water wheels were used to power irrigation systems and mills as early as the first century BCE (Rolt, 1979).

2.2 Circular Economy Principles in Antiquity

- In ancient Rome, there was zero waste since waste from one activity was frequently recycled into another. Broken ceramics were recycled, and animal and human waste was turned into fertilizer (Wilson, 2008).
- Traditional Farming Systems in China and India: Regenerative agricultural systems were developed through the cyclical utilization of animal waste and biomass (King, 1911).

3. The Modern Landscape of Renewable Energy

3.1 Solar, Wind, and Beyond

- In photovoltaics, the energy conversion efficiency of modern silicon-based solar cells has increased from less than 1% in the 1950s to more than 22% nowadays (Faiman, 2008).

- Offshore Wind Farms: In order to generate clean electricity on a big scale, new installations are essential, particularly in the North Sea and off the coast of China (IEA, 2023).
- Emerging as a fuel for industries including steel, aviation, and shipping that are challenging to electrify is green hydrogen (IRENA, 2022).

3.2 Energy Storage and Smart Grids

- Battery Technology: Solid-state and lithium-ion battery advancements have increased the dependability of renewable energy sources (Tarascon & Armand, 2001).
- Decentralized energy production and consumption are made possible by smart grids, which are crucial for combining various energy sources (Amin & Wollenberg, 2005).

4. Circular Economy in the 21st Century

4.1 Designing Out Waste

- Cradle-to-Cradle Design: End-of-life reuse is considered in the design of products (Braungart & McDonough, 2002).
- The interchange of materials and waste heat between enterprises is known as industrial symbiosis, and it may be observed in places like Kalundborg, Denmark.

4.2 The Role of Digital Technology

- Blockchain for Waste Management: Monitors material consumption and provides recycling incentives.
- IoT and AI: Used to forecast maintenance requirements, save waste, and optimize material flows (Ellen MacArthur Foundation, 2020).

5. Case Study: India's Renewable and Circular Push

India combines contemporary technologies with traditional sustainability concepts. For example, solar water pumps in rural areas of India increase crop productivity while reducing reliance on diesel.

Smart sensors are being used to resurrect traditional rainwater harvesting techniques. Plastic Recycling Hubs that use blockchain and AI sorting to provide traceability.

Conclusion:

In addition to developing new technology, the way to a sustainable future also involves revitalizing and rethinking established knowledge systems. Renewable energy-driven circular economies are a return to equilibrium with the help of innovation, not a utopian ideal. By combining traditional sustainability with contemporary research, a robust, inclusive, and long-lasting framework is produced for coming generations.

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SUSTAINABLE HEALTH SCIENCE: A FRAMEWORK FOR ENVIRONMENTAL HEALTH PROTECTION

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Introduction:

Modern technology has greatly enhanced the quality of life, making daily activities more convenient and supporting healthier living. Nevertheless, the environmental consequences of accelerated economic development, marked by excessive production, consumption, and waste generation, have led to widespread ecological problems and health risks.

Global initiatives have been launched to combat major environmental problems such as climate change, widespread pollution, and ozone depletion. In response, scientists have introduced 'Sustainability Science' to enhance these efforts. Yet, measures to address health disorders caused by environmental factors remain inadequate in Japan and worldwide. Prioritizing research on the impact of the environment on children's health is vital to protect the well-being of current and future generations.

Creation of Sustainable Health Science:

Around a century ago, Japan faced severe health challenges, with many lives lost to malnutrition and infectious diseases. This era is often considered the "Era of Public Health Enlightenment" in Japan. In 1897, Mori and Koike published the first public health textbook in Japanese, marking a significant milestone. At that time, public health efforts primarily focused on safeguarding the health of the present generation. Key initiatives included developing social infrastructure, such as sewage systems and urban planning, to enhance living conditions.

Over the past 50 years, Japan's rapid economic growth led to mass production, mass consumption, and significant waste generation, which, in turn, triggered a range of environmental issues and health disorders linked to environmental factors. To address these challenges, the concept of "Sustainability Science" emerged. This interdisciplinary field applies knowledge from various scientific domains to achieve a sustainable society. Its guiding principle is reflected in a proverb of Native American origin: "In our every deliberation, we must consider the impact of our decisions on the next seven generations."

Sustainability Science is now recognized as one of the most critical academic fields introduced in the twenty-first century. Given the urgent environmental and health challenges of our time, it must be rapidly advanced to ensure a sustainable future.

Environmental Impact of the Healthcare Industry

The healthcare industry is a significant contributor to environmental impacts worldwide. Healthcare facilities are substantial consumers of energy and various materials, and as the demand for healthcare services continues to rise, so does the environmental footprint of this sector. This growth is reflected in the increasing number of healthcare facilities and professionals, leading to higher resource consumption, greater waste generation, and a more pronounced impact on the environment.

Carbon Emissions in Healthcare

The healthcare sector is responsible for approximately **5**% of global carbon emissions**,** with the United States alone accounting for nearly 10% of its national carbon emissions. These emissions arise from various sources, including the large volume of pharmaceuticals administered, the use of chemicals in hospitals, and energy consumption in healthcare facilities.

- Surgical waste, including single-use plastics and other high-carbon materials, is a major contributor.
- Studies of large hospitals report that each kilogram of waste can emit between 345–840 g CO_2-eq (carbon dioxide equivalent).
- In Europe, the healthcare sector produces over 160 million tonnes of waste annually.

Types of Healthcare Waste

Healthcare waste is generally classified into two main categories:

1. **Hazardous Waste:** This includes medical waste that poses a risk of infection, such as used syringes, contaminated surgical instruments, and chemical waste.
2. **Non-Hazardous Waste:** This includes general waste, such as packaging, paper, and food waste.

Unfortunately, waste mismanagement is common, with hazardous and non-hazardous waste often mixed, leading to environmental contamination. For example, surgical waste is sometimes combined with household waste, increasing the risk of environmental pollution.

Energy Consumption in Healthcare Facilities

Healthcare facilities are among the most energy-intensive commercial buildings, consuming large amounts of energy for various purposes:

- **Heating, Ventilation, and Air Conditioning (HVAC):** Representing approximately **19% of total energy use**, these systems are critical for maintaining clean and controlled environments.
- **Lighting and Refrigeration:** Together account for around 75% of energy consumption in hospitals.

- **Medical Equipment and Laboratories:** Require constant power for diagnostic and therapeutic procedures.

Hospitals in the United States spend over $8 billion annually on energy, making them twice as energy-intensive as other commercial buildings. Furthermore, healthcare facilities account for nearly 19% of total material usage in the U.S., reflecting their heavy reliance on a wide range of materials.

The Role of Healthcare in Promoting Sustainability

As a major contributor to environmental impacts, the healthcare industry has a critical role in promoting sustainable practices. This involves:

- **Reducing Resource Use:** By adopting energy-efficient systems, optimizing waste management, and promoting sustainable procurement.
- **Improving Waste Management:** Implementing better waste segregation and recycling programs to minimize environmental pollution.
- **Promoting Environmental Awareness:** Ensuring that healthcare professionals lead by example, both in their practices and in the advice, they provide to patients.
- **Advocating for Sustainable Policies:** Supporting regulations that promote environmental sustainability in healthcare.

Core Principles of Sustainable Health Science

Sustainable Health Science is founded on three fundamental principles:

1. **Environmental Preventive Medicine.:** This discipline emphasizes safeguarding not only the health of people today but also that of future generations. It promotes proactive environmental improvements to prevent potential health risks, representing a modern approach to public health known as Protecting Both Current and Future Generations
2. **Adopting the Precautionary Principle:** Sustainable Health Science is grounded in a proactive mindset. It advocates for immediate action in response to early signs of potential health threats, even before their full impact becomes evident. This approach helps prevent minor issues from escalating into major health crises.
3. **Embracing Transdisciplinary Collaboration:** Recognizing that medical science alone cannot ensure sustainable health, this field encourages the integration of knowledge from various disciplines. This includes not only medical science but also architecture, engineering, and other fields that influence public health and environmental sustainability.

As part of this initiative, GSK has established sustainable sourcing standards for key materials used in its products. These include lactose, gelatin, palm oil, paper, and sugar, which are integral to the company’s drugs, inhalers, and vaccines. These materials play a crucial role in enhancing vaccine efficacy or are used in drug testing and packaging. By ensuring these materials are sustainably sourced, GSK is taking important steps towards creating a more environmentally responsible supply chain.

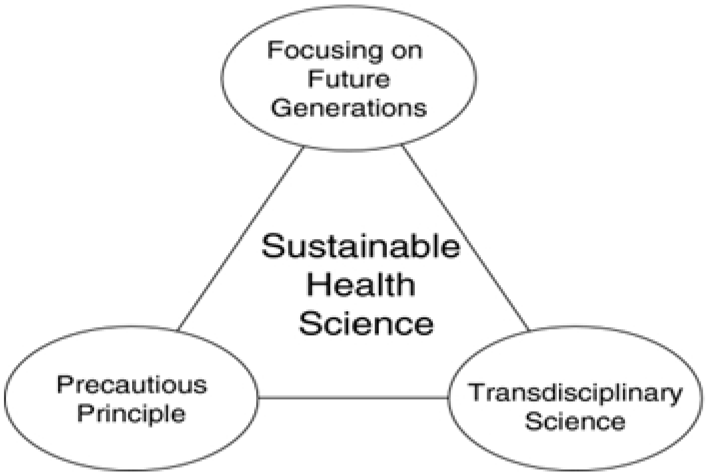

Fig. 1: Sustainable Science

Key Strategies for Promoting Sustainable Healthcare

1. **Prioritizing Sustainable Innovations:** Healthcare organizations should integrate sustainable innovations into their strategic planning, focusing on management, social policy, and health economics. This approach can enhance patient satisfaction, streamline operations, and reduce costs for healthcare providers.
2. **Fostering Effective Management:** The successful implementation of sustainable practices in healthcare depends on strong leadership and management. Organizations should invest in leadership development programs to nurture a culture of sustainability and continuous innovation.
3. **Collaborating with Stakeholders:** Sustainable healthcare practices are most effective when designed in collaboration with key stakeholders, including patients, community groups, and healthcare professionals. Engaging these groups ensures that sustainability initiatives are tailored to the community's needs.
4. **Emphasizing Social Responsibility:** Healthcare organizations should embed social responsibility into their strategic planning. By adopting socially responsible policies, they can promote sustainability and enhance cost-effectiveness in healthcare delivery.
5. **Investing in Technology:** Technology plays a vital role in sustainable healthcare. Healthcare providers should invest in digital solutions like telemedicine, electronic health records, and remote patient monitoring. These technologies can improve patient outcomes and reduce operational costs, promoting long-term sustainability.

Enhancing Recycling and Waste Diversion in Healthcare

Healthcare facilities generate significant waste during clinical procedures. To minimize environmental impact, it is essential to enhance waste sorting, recycling, and diversion strategies.

1. **Improving Waste Sorting and Recycling:** Effective waste management begins at the point of use. This can be achieved by:
   - Installing user-friendly, clearly labeled collection bins across facilities.
   - Providing consistent signage to guide proper waste disposal.
   - Offering staff education and training on waste sorting practices.

   Recycling programs can be expanded by including materials such as paper, glass, and non-hazardous plastics (e.g., pre-incision plastics) that are often discarded incorrectly. Facilities should also establish protocols for managing multi-component devices, ensuring that recyclable components are not treated as waste.
2. **Diverting Waste from Landfills and Incineration:** Reducing the volume of waste sent to landfills or incineration can lower healthcare costs. One effective approach is to repurpose or donate certain medical equipment through recognized medical charities or community organizations. However, safety and suitability must be carefully considered, particularly for single-use devices.

   This approach emphasizes the importance of maximizing product use throughout their life cycle, offering both environmental and financial benefits.

Green Building Design in Healthcare Facilities

Principle Six of the Sustainability Roadmap for Hospitals emphasizes the importance of incorporating environmental sustainability into the design and construction of healthcare facilities. Green building is defined as the practice of designing, constructing, and operating structures in an environmentally responsible and resource-efficient manner throughout their life cycle—from site selection and design to construction, operation, maintenance, renovation, and eventual deconstruction.

Core Principles of Green Building Design

Sustainable building design for healthcare facilities is guided by six fundamental principles:

1. **Optimizing Space Usage:** Minimizing the space required without compromising functionality.
2. **Sustainable Landscaping:** Designing green spaces that enhance the environment and promote biodiversity.
3. **Efficient Building Envelope:** Using materials and designs that maximize energy efficiency and insulation.
4. **Reducing Building Footprint:** Minimizing land use to preserve natural areas.
5. **Smart Infrastructure Use:** Leveraging existing infrastructure where possible.
6. **Harmonizing with Urban Form:** Ensuring that the building design complements its surrounding urban environment.

These principles are grounded in a balanced application of scientific knowledge and inspired craftsmanship. They emphasize the importance of understanding, managing, and conserving natural and built environments.

The Importance of Sustainable Design in Healthcare

Green building design in healthcare is not only about environmental sustainability but also about enhancing patient well-being. Healthcare facilities designed with sustainability in mind provide:

- **Aesthetic Comfort:** Spaces that offer a sense of solace, hope, and safety for patients.
- **Functional Benefits:** Direct links between the healing process and the surrounding environment.
- **Environmental Harmony:** A balance between ecological, socioeconomic, cultural, and individual well-being.

Sustainable healthcare building designs include multiple critical elements:

- **Energy Efficiency:** Reducing energy consumption through advanced systems and technologies.
- **Optimal Life Cycle Cost:** Minimizing costs over the building's life span.
- **Adaptability:** Designing spaces that can accommodate evolving medical technologies.
- **Durable Materials:** Using high-quality, long-lasting materials.
- **Environmental Quality:** Maintaining optimal air and water quality for occupants.
- **Waste Management:** Implementing efficient logistics for waste reduction.
- **Infection Control:** Enhancing safety through design elements that minimize the spread of diseases.
- **Security Measures:** Ensuring a safe and secure environment for patients and staff.

The Benefits of Green Building in Healthcare

Sustainable design in healthcare provides multiple advantages, including:

- Reduced environmental impact, preserving natural resources and minimizing pollution.
- Enhanced indoor air quality, creating a safer and more healing environment for patients.
- Lower operational costs, including savings on energy, water, and waste management.
- Increased staff satisfaction and productivity due to improved working conditions.
- Faster patient recovery, supported by a health-promoting physical environment.

Carbon Emissions and Waste Generation in Healthcare

The healthcare industry is a significant contributor to global carbon emissions and waste generation. Healthcare facilities rely heavily on energy-intensive systems, including heating, ventilation, and air conditioning (HVAC), as well as the continuous use of medical devices and pharmaceuticals. These activities consume large quantities of clean water and energy, leading to substantial greenhouse gas emissions. Globally, healthcare buildings account for approximately 5% of total emissions, with hospitals in high-income regions being particularly significant contributors. A study estimated that healthcare facilities produce around 12 million tonnes of waste worldwide, roughly equivalent to one tonne of waste per hospital bed. This waste can be categorized into two main types: general waste, which is relatively harmless to public health and the environment (such as cardboard and packaging), and biomedical waste, which includes hazardous materials like surgical gloves and infectious waste requiring special handling.

The balance between these waste types often reflects the quality of healthcare provided, as poor waste management can compromise both patient safety and environmental sustainability. To reduce the carbon footprint of healthcare facilities, it is essential to improve waste management, optimize energy use, and promote sustainable practices—steps that can simultaneously enhance public health outcomes and mitigate climate change.

Conclusion:

Rapid economic growth has led to an increase in health disorders caused by environmental factors. As we move further into the twenty-first century, it is increasingly recognized as the era of preventive medicine. Recent scientific investigations have focused on understanding the relationship between the environment and human health. From these studies, the academic field of "Sustainable Health Science" has emerged. This new discipline aims to address and mitigate environmental health risks, contributing to the creation of a healthier environment for future generations.

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ADAPTIVE TRAITS OF THAR DESERT PLANTS FOR SURVIVING ARID CONDITIONS

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Introduction:

The Thar Desert, also known as the Great Indian Desert, spans approximately 200,000 square kilometers across northwestern India and eastern Pakistan, with over 60% of its area in the Indian state of Rajasthan. Characterized by extreme aridity, low and erratic rainfall (100–500 mm annually), high evapo-transpiration, and temperatures ranging from near-freezing in winter to over 50°C in summer, the Thar Desert presents one of the most challenging environments for plant survival. Despite these harsh conditions, the region supports a surprisingly diverse flora, with over 628 plant species from 352 genera and 87 families, adapted to withstand acute drought, sandy soils, and intense sunlight. This chapter explores the mechanisms of drought resistance in plants of the Thar Desert, focusing on their physiological, morphological, and ecological adaptations, and highlights key species and their significance for conservation and sustainable agriculture.

Environmental Challenges of the Thar Desert

The Thar Desert's climate is subtropical and arid, driven by persistent high pressure and the bypassing of monsoon winds, resulting in minimal precipitation. Rainfall is highly variable, often concentrated in a short July-to-September monsoon, with some areas receiving less than 250 mm annually. Soils are predominantly sandy, with low organic matter, high salinity, and poor water retention, exacerbating water scarcity. Wind erosion and shifting sand dunes further challenge plant establishment, while high solar radiation and extreme diurnal temperature fluctuations impose additional stress. These conditions necessitate specialized adaptations for plants to survive and reproduce.

Mechanisms of Drought Resistance

Plants in the Thar Desert employ a range of strategies to cope with water scarcity and environmental stress. These adaptations can be broadly categorized into morphological, physiological, and ecological mechanisms.

Morphological Adaptations

- **Reduced Leaf Surface Area**: Many Thar Desert plants, such as *Prosopis cineraria* (khejri) and *Capparis decidua* (ker), have small or no leaves to minimize transpiration.

For example, *Prosopis cineraria* has bipinnate leaves with tiny leaflets, reducing water loss while maximizing photosynthetic efficiency.

- **Deep Root Systems**: Deep roots allow plants to access groundwater or moisture stored in lower soil layers. *Calligonum polygonoides* and *Ziziphus mauritiana* (ber) develop extensive root systems, sometimes reaching depths of several meters, to tap into scarce water resources.
- **Water Storage Tissues**: Succulent plants like *Euphorbia caducifolia* and *Opuntia spp.* store water in thickened stems or leaves, enabling survival during prolonged dry periods. These tissues are often covered with waxy cuticles to prevent desiccation.
- **Spines and Thorns**: Thorns, as seen in *Acacia nilotica* (babool) and *Ziziphus nummularia*, reduce water loss by replacing leaves and deter herbivory, conserving resources in a resource-scarce environment.
- **Ephemeral Life Cycles**: Many grasses and herbaceous plants, such as *Cenchrus biflorus* and *Aristida spp.*, are ephemerals, germinating rapidly during brief rainy periods and completing their life cycles before the soil dries out, leaving drought-resistant seeds.

Physiological Adaptations

- **Efficient Water Use**: Plants like *Prosopis cineraria* exhibit high water-use efficiency, optimizing photosynthesis while minimizing transpiration through stomatal regulation. Crassulacean Acid Metabolism (CAM) photosynthesis, observed in some succulents, allows nocturnal carbon fixation, reducing daytime water loss.
- **Osmotic Adjustment**: Species such as *Salvadora oleoides* and *Tamarix spp.* accumulate osmolytes (e.g., proline, sugars) to maintain cell turgor under low water availability, enabling continued metabolic activity during drought.
- **Drought Tolerance**: Many plants, including *Commiphora wightii* (guggul), a critically endangered species, tolerate extreme dehydration by entering dormancy or shedding leaves during dry periods, resuming growth when water becomes available.
- **Salt Tolerance**: In saline flats, halophytes like *Suaeda fruticosa* and *Salsola baryosma* thrive by accumulating salts in their tissues or excreting them through specialized glands, maintaining water uptake in high-salinity soils.

Ecological Adaptations

- **Community Interactions**: Plants in the Thar Desert often form associations that enhance survival. For instance, *Prosopis cineraria* acts as a nurse plant, providing shade and improving soil fertility for understory species like *Crotalaria burhia*.
- **Seed Dispersal and Dormancy**: Many species produce seeds with hard coats or dormancy mechanisms, ensuring germination only under favorable conditions. *Ziziphus*

mauritiana seeds, for example, remain viable in the soil for years, germinating after sufficient rainfall.

- **Mycorrhizal Associations**: Some plants, such as *Acacia senegal*, form symbiotic relationships with mycorrhizal fungi, enhancing water and nutrient uptake in nutrient-poor soils.

Key Drought-Resistant Plant Species

Several plant species epitomize the resilience of Thar Desert flora, playing critical ecological and socio-economic roles:

- ***Prosopis cineraria* (Khejri)**: Known as the "king of the desert," this tree is a lifeline for local communities, providing fodder, fuel, and shade. Its deep roots and small leaves make it highly drought-resistant, and it supports biodiversity by stabilizing soil and hosting epiphytes.
- ***Capparis decidua* (Ker)**: This shrub thrives in sandy soils with minimal water, producing edible fruits used in local cuisine. Its leafless, spiny structure reduces transpiration, and genetic studies reveal high diversity, aiding conservation efforts.
- ***Ziziphus mauritiana* (Ber)**: A drought-tolerant fruit tree, it provides nutritious berries and fodder. Its deep roots and waxy leaves enable survival in arid conditions, making it a candidate for agroforestry.
- ***Calligonum polygonoides* (Phog)**: A psammophytic shrub, it stabilizes sand dunes and survives extreme drought through deep roots and reduced leaf surface area. Its chemical diversity supports medicinal applications.
- ***Commiphora wightii* (Guggul)**: This critically endangered shrub is valued for its medicinal resin but faces overexploitation. Its drought tolerance stems from succulent stems and dormancy mechanisms.
- ***Cenchrus biflorus* (Bhurat)**: An ephemeral grass, it rapidly colonizes dunes during monsoons, providing fodder and preventing erosion. Its seeds remain dormant during dry periods.

Socio-Economic and Ecological Importance

Drought-resistant plants in the Thar Desert are integral to the livelihoods of local communities, who rely on them for food, fodder, fuel, and medicine. *Prosopis cineraria* and *Ziziphus mauritiana* support agroforestry, enhancing food security and soil fertility. Medicinal plants like *Commiphora wightii* and *Capparis decidua* contribute to traditional healthcare and local economies. Ecologically, these plants stabilize sand dunes, reduce soil erosion, and support biodiversity, including endangered species like the Great Indian Bustard. However, invasive species like *Prosopis juliflora* threaten native flora, disrupting ecosystems and reducing grazing land.

Conservation and Sustainable Utilization

The Thar Desert's flora faces threats from desertification, overgrazing, mining, and climate change, which exacerbate drought and reduce rainfall predictability. Conservation efforts include:

- **Protected Areas**: The Desert National Park in Jaisalmer and Barmer conserves native flora and fauna, protecting species like *Commiphora wightii* and *Tecomella undulata*.
- **Afforestation Initiatives**: Programs led by organizations like SankalpTaru Foundation promote planting native species such as *Prosopis cineraria* and *Ziziphus mauritiana*, engaging communities in sustainable agroforestry.
- **Traditional Water Conservation**: Techniques like khadins and johads harvest rainwater, supporting agriculture and revegetation with drought-resistant crops like millets and pulses.
- **Biotechnological Approaches**: Tissue culture and genetic studies, as conducted on *Capparis decidua* and *Calligonum polygonoides*, aid in conserving endangered species and developing drought-tolerant varieties.

Challenges and Future Directions

Despite their resilience, Thar Desert plants face challenges from invasive species, habitat loss, and unsustainable land use. *Prosopis juliflora*, introduced for dune stabilization, has become invasive, outcompeting native species and reducing biodiversity. Climate change further threatens flora by increasing drought frequency and altering monsoon patterns. Future research should focus on:

- Developing drought-resistant crop varieties through breeding and genetic engineering.
- Restoring degraded ecosystems by removing invasive species and replanting natives.
- Integrating traditional knowledge with modern conservation practices to enhance community participation.
- Expanding protected areas and enforcing sustainable land-use policies.

Conclusion:

The plants of the Thar Desert exemplify remarkable adaptations to one of the world's harshest environments. Through morphological, physiological, and ecological strategies, species like *Prosopis cineraria*, *Capparis decidua*, and *Ziziphus mauritiana* not only survive but thrive, supporting ecosystems and human livelihoods. Conservation and sustainable utilization of these drought-resistant plants are critical for combating desertification, ensuring food security, and preserving biodiversity in the face of climate change. By combining traditional practices with modern science, the Thar Desert's flora can continue to serve as a model of resilience and adaptation.

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ZEOLITE APPLICATION FOR SUSTAINABLE AGRICULTURE

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Historical Perspective and Discovery

Zeolites were first identified in 1756 by Swedish mineralogist Axel Fredrik Cronstedt, who observed that heating the mineral stilbite caused it to emit steam, indicating water release from the structure (Encyclopaedia Britannica, 2025). Inherently, natural zeolite originated when volcanic rocks and layers of ash come in contact with ground water and lakes that are alkaline or saline in nature.

Among the different zeolite chabazite, erionite, mordenite and clinoptilolite are the major examples of naturally occurring commercially used adsorbent zeolites.

Categorization of Zeolite

Previously, the zeolites are categorized on the basis of their morphological features. But currently, the base that is taken into consideration for classifying the zeolite is the secondary structure units of its armature. Other than these, crystal lattice arrangement, effective pore size, mode of occurrence, chemical constituent and Si: Al ratio are also used to classify the zeolite.

Zeolites are characterized on the basis of silica: alumina ratio as given below:

Class	Si: Al
Low	1.0 to 1.5
Intermediate	1.5-8
High	>10

Increased Si/Al ration increases the hydrophobic nature and thermal stability whereas, decreasing the cation content in zeolite.

The more Si: Al ratio indicates more catalytic activity. This is because with the increase in silicon to aluminium ratio acidic sites in zeolite decreases. On the other hand, effectiveness of each acidic site increases.

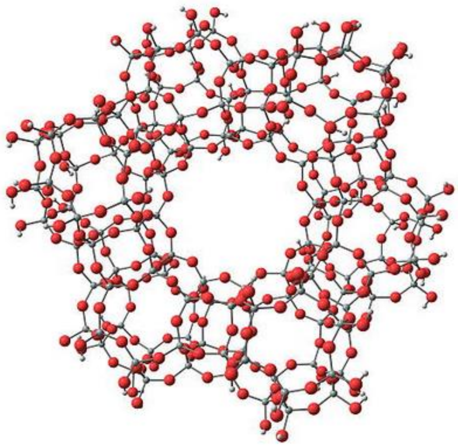
Zeolite saturated with alumina and low in silica mainly exhibit a large number of cation exchange sites which helps in balancing the structural aluminium, and this results in the highest cation contents and cation exchange capacities of zeolite. Whereas intermediate Si containing zeolite shows more stability than high and low Si containing zeolites.

Zeolites are characterized based on pore size diameter as given below: (Flanigen, 2001).

Class	Number of Ring	Diameter in nm
Small pore Zeolite	8- Rings	0.3-0.45 nm
Medium Pore Zeolite	10- Rings	0.45-0.6 nm
Large pore zeolite	12-Rings	0.6-0.8 nm
Extra-large Pore Zeolite	14-Rings	0.8- 1.0 nm

Chemical formula and Configuration of Zeolite

A three-dimensional arrangement of Silicon, oxygen and aluminium atoms in a tetrahedral fashion forms the basic structure of zeolite. Zeolite mainly contains two sub units one is fused rings column and second is the inner space region between these columns.



In zeolite crystal lattice, the isomorphous substitution of Al^{3+} ion for Si^{4+} causes a charge imbalance and consequently, large cavities of the framework require other monovalent and divalent cations viz. Na^{+}, K^{+} and Mg^{+} etc. to stabilise this charge imbalance. Structurally, zeolites are very similar to feldspar mineral except that in zeolite configuration, large-sized voids and more water are found (The Editors of Encyclopaedia Britannica, 2025).

Effect of Natural Zeolite Application on Soil Physical, Chemical and Biological Properties

The main three characteristics of Zeolite i.e. high CEC, high adsorption ability and high water retentivity or holding capacity encourages the use of zeolite in Agriculture. However, according to the report of International Agency for research on cancer (IARC) declare that zeolite is non-toxic and safe for human consumption which increase the opportunities for its uses in agriculture.

Among the 50 natural occurring zeolites, the well-known groups are clinoptilolite, chabazite, mordenite, erionite, stilbite, heulandite, and phillipsite. Out of all these clinoptilolite is most frequently used in Agriculture sector (Polat *et al.*, 2004).

1. **Soil pH:**

Zeolite raises the soil pH, i.e., in soil, Fe and Al hydroxides cause soil acidity, and zeolites can absorb these ions. Basic cations like Ca, Mg, K etc. released by zeolites. As a result, soil acidity decreases, and it can be used as an amendment to neutralize soil acidity. Details of some research works supporting the above statement are depicted below.

Minardi *et al.* (2020) experimented on the incorporation of manure and zeolite and their effect on soil chemical properties and soybean yield and found that a rise in pH can be seen on adding zeolite, and it is about 3% more than the control plot.

Ravali *et al.* (2020) studied on introduction of zeolite and their effect on soil properties and stated that the highest soil pH is recorded with the highest dose of zeolite application.

According to a few other researchers, there is a small change in soil pH on applying zeolite. Szatanik-Kloc *et al.* (2021) experimented on outcome of low zeolite doses on soil physico-chemical properties and revealed that soil pH increased after applying the maximum zeolite dose.

Baddour & El-Kafrawy (2020) stated in a research paper that changes in soil pH are minimal on applying zeolite with different treatments. This type of contrary result can be due to the buffering capacity.

2. **Electrical Conductivity:**

Zeolite addition introduces alkaline cations into the soil solution, thereby elevating electrical conductivity (EC). Baddour & El-Kafrawy (2020) reported increased soil salinity at maize harvest due to higher EC, which could be mitigated through irrigation. The soil salinity can be reduced by applying irrigation, which helps to leach down the accumulated salt.

3. **Bulk Density:**

Porosity shows an increasing pattern on application of zeolite in soil due to the presence of the crystalline structure of zeolite. As a result, bulk density decreases. Information about some research work that supports the above statements is given below.

Ravali *et al.* (2020) found that zeolite-treated soils had noticeably lower bulk density than untreated soils. Similarly, Abdel-Hassan & Radi (2018) recorded significant reductions in sandy soils.

4. **Water Holding Capacity:**

Zeolites contain more micropores in their absorbent crystalline structure. It can hold water in the interlayer pore spaces, which shows increasing water holding capacity on zeolite application.

Ravali *et al.* (2020) stated that application of maximum dose of zeolite can able to increase the water retention over the control treatment. Due to zeolite application, increasing water holding capacity denotes more available water content in the soil.

Abdel-Hassan and Radi (2018) in their research findings recorded that available water can be increased through the application of zeolite by increasing porosity and reducing bulk density.

5. CEC:

Due to isomorphous substitution, zeolites contain negatively charged sites that attract exchangeable cations. As a result, zeolites have higher CEC, thus increasing the CEC of the soil. Baddour & El-Kafrawy (2020), in their research findings, support the following statement.

Ravali *et al.* (2020) experimented on introduction of zeolite and their effect on soil properties and obtained that maximum zeolite application shows an increasing CEC compared to the control plot, which shows a significant result.

Minardi *et al.* (2020) worked on incorporation of manure and zeolite and their effect on soil chemical properties and soybean yield and stated that maximum CEC is recorded on the application of zeolite and it shows an increase over the control plot.

6. Hydraulic conductivity:

According to some research findings, hydraulic conductivity decreases on adding zeolite in sandy soil, but for mixed soil, hydraulic conductivity increases on application of zeolite. Abdel-Hassan & Radi (2018) in a research paper, published about the effect on hydraulic conductivity on application of zeolite in different soils.

7. Soil Microbial Activity:

Basal respiration induces the mineralization of organic matter through microorganisms, and it is the quantification of CO_2 emission from soil.

The maximum CO_2 emission is noted on the application of the maximum dose of mechanically activated zeolite (Bikkinina *et al.,* 2020).

Paliaga *et al.* (2025) in their research stated that favorable bacteria are implemented by applying biochar coupled with zeolite.

8. Enzymatic Activity:

Zeolite itself has a catalytic action and promotes catalytic activity in combination with biocatalyst enzymes (Zhang *et al.,* 2021). Few factors are responsible for varying the enzymatic activities in soil with zeolite application.

It is recorded that the acid phosphatase activity is decreased thoroughly on applying zeolite in soil due to zeolite application helps to increase the soil pH (Sindesi *et al.,* 2024).

Beta-glucosidase activity is also decreased on application of zeolite, it may be due to lower organic carbon content (Sindesi *et al.,* 2024).

Conclusion:

Changes in different properties of soil due to the application of zeolite are significant. The pH change by zeolite can support its future use as an acidic soil amendment. Zeolite application significantly increases the cation exchange capacity of soil, which can hold more nutrients and supply essential nutrients to the plant. As a result, it reduces nutrient leaching, thereby application of zeolite can be significant in sandy, low fertile soils. Due to its porous structure, water retention is higher in zeolite-applied soil, which can support drought resistance and can be better for plant growth.

Besides nutrient management, zeolite also improves soil structure, enhances plant growth, and easier root penetration. Zeolites induce sustainable soil management for long-term stability, further enhancing soil fertility.

Zeolite as a soil amendment holds the potential for future aspects of sustainable land management, stabilizing long-term fertility, and others. However, its initial cost of the application is much higher, but its agronomic benefits, soil amendment properties, and environmental benefits make zeolite a promising amendment for enhancing crop productivity, sustainable soil management, and future use.

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EFFECTIVENESS OF AI-BASED LESSON PLANNING TOOLS FOR TEACHERS: A REVIEW

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Abstract:

Artificial Intelligence (AI) continues to transform the educational field by creatively providing ways to improve the lesson plan and teaching methods. This study examines the effects of AI-driven lesson preparation tools on teacher productivity, in addition to enhancements in student engagement and instruction quality. Platforms driven by artificial intelligence, such as ChatGPT, IBM Watson Education, and Google's AI for Education, can automate course design while providing a range of materials and individualized learning opportunities. Although AI technologies lessen the workload of teachers and enhance tailored learning, they still have challenges with algorithmic bias, privacy, ethical data collection, and the potential for over-reliance. The degree to which teachers are comfortable with the technology and have access to continual professional development opportunities will determine how well artificial intelligence is implemented in classrooms. To figure out the potential pros and cons of AI technology in educational settings, this work provides an in-depth literature review. To maintain teaching methods that relate to students' emotions, treat all learners equally, and remain relevant in certain circumstances, the study highlights that effective teaching requires the combination of AI tools and human instructors' expertise. Research should address ethical concerns while evaluating AI's cultural adaptation and tracking its long-term impacts on students' capacity for creativity and critical thought. When applied carefully and intelligently, AI may transform lesson planning and improve learning results, guaranteeing long-term success.

Keywords: Artificial Intelligence in Education, AI-Based Lesson Planning, Teacher Effectiveness, Instructional Technology, Personalized Learning, Educational Innovation, Ethical Issues in AI, Student Engagement, Professional Development, Data Privacy.

Introduction:

The inventor of artificial intelligence, John McCarthy, describes it as *"the science and engineering of making intelligent machines, especially intelligent computer programs."* The capacity for computers, computer-controlled bots, or software to be made to reason and think similarly at the level of a human being is termed Artificial Intelligence. Artificial Intelligence is made possible by studying how the human brain operates, how individuals learn, make choices, and how they go about the activity of problem-solving.

The findings from this study are then implemented in the creation of advanced software and systems. While thinking about how computer systems can be utilized alongside human inquisitiveness, he asked, "Is it possible for a machine to think and act like a human?" Therefore, the objective of building AI technologies was to make computers have the same amount of intelligence that humans greatly admire. The branches of knowledge on which the technology of AI is based are computer science, biology, psychology, linguistics, mathematics, and engineering.

An essential goal of artificial intelligence is to emulate human abilities in computers – teaching, reasoning, and problem-solving. Due to AI systems' predicting, diagnosing, recommending, and decision-making capabilities (Hwang *et al.*, 2020a), the education sector started to take an interest in AI, particularly for multi-context learning facilitation.

Artificial intelligence in education (AIEd) has been a field of technological advancements, theoretical developments, and positive pedagogical effects (Roll & Wylie, 2016). Its applications include intelligent tutors for content delivery, feedback providing, and progress supervision (Bayne, 2015). The advantages of AIEd are well known; it is progressively changing the nature of education by giving educators new avenues for connecting with and helping their students on a more personal level. Learning becomes more efficient and interesting when teachers use AI tools to customize lessons and learning resources to each student's unique needs instead of depending just on conventional approaches. For example, AI can assist in pinpointing the precise regions in which a student is having difficulty by detecting comprehension gaps, which can be challenging to do in a crowded classroom (Guan *et al.*, 2020). Chen *et al.* (2021) claim that these technologies do more than just customize content; they also use advanced algorithms to assess students' skills and knowledge in real time, providing them with relevant feedback that enhances progress monitoring for both teachers and students. Additionally, AI can analyze student involvement and classroom behavior, making identify when a kid may be lagging is simpler. With this insight, teachers can step in early and provide student support, possibly preventing future academic struggles (Tsai *et al.*, 2020).

AI in Education:

The subject of educational technology development is dynamic, always evolving, and generating new concepts. Beginning with traditional tools like projectors and whiteboards, technological developments have completely transformed education. With the introduction of computers into classrooms, students entered a new era where they could access material that was previously inaccessible, engage in interactive learning, and instantly jump online. By overcoming geographic barriers, the widespread use of the internet further democratized knowledge and encouraged global connectivity in education (Baidoo-Anu, D., & Ansah, L.O., 2023). As we moved into the digital age, learning management systems, e-learning platforms, and interactive whiteboards became more common, transforming the educational landscape. A patchwork of digital tools, such as cloud-based collaboration, virtual and augmented reality, and learning analytics that offer data-driven insights, make up today's educational technology. This consolidation has made the learning environment more personalized and interactive. Future advancements such as machine learning (ML) and artificial intelligence (AI) are anticipated to set the standard and have the power to fundamentally alter education. We discover a tale of innovation in educational technology development that has profoundly influenced how knowledge is acquired and disseminated (Castelli, M., & Manzoni, L., 2022).

Many of the goals for enhancing teaching and learning are not being achieved today. To meet these priorities, educators look for technologically sophisticated, scalable, and safe methods. It should go without saying that educators are curious about the potential benefits of the quick changes in technology in everyday life. Like everyone else, educators use AI-powered services in their daily lives, including voice assistants for their homes, trip planning apps for smartphones, and tools that can compose essays, correct grammar, and finish sentences. Many educators are actively researching AI tools as they become more accessible. One Educators see opportunities to use AI-powered features like speech recognition to increase the support given to children with disabilities, multilingual learners, and others who can gain from greater flexibility and personalization in digital learning tools. They are looking into how they find, select, and alter content for their classes, as well as how AI might assist them in creating or improving lessons. Teachers are also aware of new threats. Strong, useful features could also have extra privacy and security risks. Teachers are aware that AI can produce inappropriate or inaccurate results on its own. They are concerned that unintended biases may be amplified by the associations or automations produced by AI. They have observed fresh ways in which pupils could pass off other people's work as their own. They are fully aware of pedagogical techniques and "teachable moments" that a human teacher can address but that AI models miss or misinterpret. They are concerned about the fairness of algorithmic recommendations.

Scientific output on AIEd has significantly increased as a result of practitioners and researchers leveraging AI's pedagogical potential and advocating for it (Hinojo-Lucena *et al.*, 2019). Methods for examining scientific literature include identifying research themes, evaluating scientific collaborations, and identifying research motives. It aids in a thorough comprehension of the past and present of a subject (Chen *et al.*, 2020a). Since AIEd research is growing quickly, it makes sense to compile the body of existing literature into a concise review. Several reviews have used the systematic analysis of small samples or narrative synthesis. AIEd literature was examined by Chassignol *et al.* (2018) from four angles: student-teacher communication, technology-assisted assessment, creative teaching strategies, and personalized learning materials. Their analysis was based on 47 articles that were published in the International Journal of Artificial Intelligence in Education (IJAIED) in 1994, 2004, and 2014. Roll and Wylie (2016) found in their investigation of AIEd's benefits and potential that there was a revolutionary process in the adoption of AI technologies in students' everyday life and community activities, as well as an evolutionary process in how a variety of AI technologies helped in-class learning practices and interactions with teachers. Zawacki-Richter *et al.* (2019) systematically reviewed 146 publications on artificial intelligence (AI) in higher education and found that AI can be used for intelligent tutoring systems (ITSs), assessment and evaluation, adaptability and personalization, and profiling and prediction to support academic, institutional, and administrative services.

AIEd has undergone quantitative analysis. Goksel and Bozkurt (2019) studied AIEd publications released between 1970 and 2018 using social network analysis. Three themes surfaced: learning styles and adaptability/personalization; expert systems and ITSs; and artificial intelligence as a component of education all around. Hinojo-Lucena *et al.* (2019)'s bibliometric analysis of 132 AIEd papers from 2007 to 2017 revealed that the period was an early stage for publications in the field and that AIEd was of global interest. Chen *et al.* (2020b) investigated 45 AIEd-related publications using annual distribution analysis, important journals, institutions, countries/regions, research issues, and underlying theories and technologies to expose gaps in AIEd theory and applications. Guan *et al.* (2020) searched 400 papers on artificial intelligence (AI) and deep learning (DL) in education using keyword analysis and human coding. Between 2000 and 2009, there was a development.

From 2010 to 2019, learner profiling and learning analytics (LA) supported individualized learning, interest in planning and implementing online education. Tang *et al.* (2021) carried out a thorough assessment of publications regarding the use of AI in e-learning, focusing on leading journals, countries, disciplines, and applications. They did this by using a co-citation network analysis, which examined the relationships between core-cited references to predict future research orientations. Their review found that Bayesian networks were widely used for AI-based customized learning scenarios and for predicting student characteristics. The majority of reviews have employed qualitative techniques, examining only a small number of papers and particular findings. This prevents them from providing a comprehensive grasp of the subject overall, especially in regards to study themes and topic development. This manual coding and synthesizing approach to examining a publication's full contents, however, is becoming increasingly laborious, difficult, and outdated as the volume of published material grows quickly.

AI for Lesson Planning:

Since artificial intelligence (AI) entered the classroom, lesson preparation has evolved along with other aspects of teaching and learning. Teachers must create assessments, come up with interesting activities, and match curricular requirements with learning objectives as part of the time-consuming traditional lesson planning process. This method could be too much for teachers who are new to teaching or who are teaching multiple courses. One practical strategy to increase educational quality, reduce teacher workload, and speed up these processes is the deployment of AI-based lesson preparation tools (Holmes & Tuomi, 2022).

Natural language processing (NLP), data analytics, and machine learning algorithms are all combined in artificial intelligence (AI)-driven lesson planning systems to produce well-organized lesson plans, recommend relevant teaching materials, and provide teachers with real-time feedback. Through automated recommendations based on students' learning needs, these tools assist teachers by facilitating differentiation and customized education. By analyzing data on student performance, AI-based solutions can also recommend changes to lesson plans, guaranteeing a more flexible and responsive teaching style (Kehoe, 2023).

Teachers may also create more dynamic and captivating lesson plans that support creative teaching techniques by utilizing AI technology. Some AI-powered platforms that provide teachers with useful materials, such as question banks, activity ideas, and sample lesson templates, are ChatGPT, IBM Watson, and Google's AI for Education. According to Lee and Zhai, these resources can be altered to meet a variety of educational needs. They can also help teachers plan lessons by encouraging a culture of best practices and knowledge sharing, which facilitates the sharing and improvement of lesson ideas through online communities.

Despite its advantages, there are drawbacks to using AI in lesson planning. The proper use of AI in education is called into question by worries about algorithmic biases, ethical implications, and data privacy. Teachers who lack the requisite training or who are averse to technological change may also find it difficult to adapt to AI technologies. Furthermore, the effectiveness of AI-generated lesson plans may vary depending on the environment because they are often developed using traditional curriculum, which restricts their flexibility to certain educational contexts (Kanvaria & Ritika, 2024).

The purpose of this systematic study is to assess the usefulness of AI-based lesson preparation tools by examining their effects on teacher effectiveness and instructional quality. It also looks at the benefits and challenges of these technologies and identifies potential research directions. By reviewing significant literature, this study provides insights into how AI is evolving in education and how this will affect pedagogical methods. While addressing the challenges and limitations associated with its use, the review's findings will advance our understanding of how AI can be most successfully integrated into lesson design.

Table 1 compares leading AI tools used in education, focusing on their features, strengths, and limitations relevant to lesson planning activities.

Table 1: Popular AI Tools Supporting Lesson Planning and Their Key Attributes

AI Tool	Key Features for Lesson Planning	Strengths	Limitations
ChatGPT (OpenAI)	- Generates lesson ideas, quizzes, writing prompts - Provides differentiated content suggestions	- Highly flexible - Supports inquiry-based learning	- May generate inaccurate content - No curriculum alignment guarantee
IBM Watson Education	- Personalizes learning resources based on student profiles - Recommends adaptive lesson plans	- Strong data analytics - Good for STEM and skill development	- Requires high-quality input data - Complex setup
Google AI for Education	- Assists in resource curation (Google Classroom integration) - Supports multilingual lesson aids	- Easy integration with existing digital classrooms	- Limited deep lesson customization - Focuses more on resource delivery than full planning
Knewton	- Adaptive learning pathways - Recommends lesson adjustments based on mastery patterns	- Strong for personalized, student-centered instruction	- Primarily designed for specific subjects (like math)
Squirrel AI	- Intelligent tutoring system for student diagnostics - Recommends lesson sequencing	- Effective for at-risk student intervention	- Mostly used in Asian education contexts; limited global customization

Objective of the study:

The objective of this research is to evaluate the efficiency of AI in this activity by observing how teachers can properly design and organize their lesson plans with the assistance of AI-based technologies. The effect of AI-informed lesson planning on efficient teaching is also analyzed to determine if this technique improves the teaching process and student engagement. In addition, this research examines how AI can assist in personalizing and adapting lesson materials, delving into how it can aid individualized learning experiences through modifying lesson plans in conformity with the specific needs of every individual student. Moreover, the research examines the limitations and drawbacks of AI-informed lesson planning tools, noting possible risks, stereotypes, and ethical issues related to the use of AI in education.

Review of Related Literature:

Impact on Instructional Quality and Teacher Effectiveness

Generative AI technologies notably improve lesson planning in teacher training by elevating instructional effectiveness, lesson clarity, and overall teaching productivity, Kehoe (2023) states. Educators are supported by AI-enabled tools to align learning goals with curriculum needs, keeping lesson plans organized, pertinent, and pedagogically correct. Such technologies allow teachers to create well-structured, multifaceted lessons that accommodate different learning modes and education standards.

Kehoe also highlights how AI-based platforms give pre-service teachers instant feedback on the organization, clarity, and coherence of their lesson plans. These smart tools review lesson elements, detect inconsistencies, and recommend improvements in instructional sequencing, pacing, and engagement strategies. Through instant, data-driven feedback, prospective teachers can iteratively improve their teaching practices, making their lessons clear, well-organized, and effective.

The incorporation of generative AI in teacher training not only maximizes lesson planning but also empowers educators with high-level tools to improve their teaching efficiency. Utilizing AI-supportive assistance, pre-service and in-service teachers alike can develop more vibrant, consistent, and interactive lessons that lead to better student learning results and classroom experiences.

•Lee and Zhai (2024) discuss how ChatGPT can be utilized to plan science lessons, highlighting the improvements in content generation, flexibility, and differentiated learning experiences. Their research explains how AI-based platforms such as ChatGPT enable teachers to create systematic yet dynamic lesson plans that can accommodate different learning requirements. Teachers can create explicit explanations, interesting discussion points, and tailored assessments based on students' differences in skills. In addition, AI allows for differentiated instruction through adjusting content difficulty, offering scaffolding for struggling students, and challenging advanced learners with challenging problems.

Due to its adaptability, ChatGPT allows science teachers to support multiple learning styles, thus enhancing the accessibility, inclusivity, and interest of their lessons. The research also highlights that AI-supported lesson planning facilitates inquiry-based learning by creating interactive, real-world contexts that engage students to reason critically, question, and solve problems. Moreover, AI can assist teachers in compiling the latest scientific facts, planning virtual experiments, and providing instant feedback, which eventually enhances the overall learning experience.

Van den Berg and du Plessis (2023) examine the transformative role of artificial intelligence (AI) in fostering critical thinking, adaptability, and openness in teacher education. According to their research, AI-powered solutions enhance instructional design while also increasing the productivity, preparedness, and professional growth of instructors. Teachers can become more adept at critical thinking and evaluating their lesson ideas and delivery by integrating AI into their training programs. This will help them adjust to a variety of classroom settings.

One of the primary conclusions of the study is that AI can support reflective teaching practices. AI-powered platforms review lesson structures, providing teachers with useful data regarding the coherence, pacing, and effectiveness of their instructional strategies. By identifying possible issue areas, such as disparities in learning objectives, gaps in the way the information is given, or low participant engagement, artificial intelligence (AI) helps teachers improve their techniques and raise the bar for their classes. Teachers regularly assess their methods and make data-driven adjustments to optimize student learning. This strategy encourages a culture of continuous professional development.

Benefits of AI-Assisted Lesson Planning

Muhammadi *et al.* (2025) provide an interesting discussion of the application of artificial intelligence (AI) in the preparation of English as a Foreign Language (EFL) lesson, emphasizing how AI can enhance resource accessibility, boost instructor involvement, and create more dynamic learning environments. According to their research, teachers may quickly prepare lessons and ensure that the content is appropriate for students' skill levels by using AI-assisted technologies that provide them with access to a vast library of lesson plans, interactive activities, and language-specific teaching methodologies. By integrating a range of multimedia elements that cater to various learning styles, including audio snippets, videos, and interactive exercises, AI-powered solutions assist instructors in developing more effective lesson plans. Enhancing student involvement in EFL instruction through personalized and flexible learning experiences is a significant benefit of AI-powered systems.

By looking at students' learning styles, language proficiency, and problem areas, teachers can modify their instruction. AI offers students real-time feedback and adaptive suggestions to help them overcome language difficulties through interactive reinforcement of vocabulary, grammar, and pronunciation. Furthermore, by mimicking conversational scenarios, AI chatbots and virtual tutors help students practice their English in authentic contexts and enhance their fluency outside of the academic setting.

Muhammadi *et al.* (2025) assert that AI is also essential in choosing contextually relevant and culturally suitable materials for EFL training. When AI suggests lessons based on linguistic patterns and cultural peculiarities that relate to students' backgrounds, language learning becomes more approachable and meaningful. This guarantees that EFL lessons are inclusive, interesting, and grammatically correct while also encouraging pupils to comprehend other cultures. Additionally, AI-powered translation tools facilitate clear comprehension and communication between teachers and students in multilingual classrooms by assisting them in overcoming language hurdles.

In addition to delivering courses, AI helps teachers grow professionally by improving instruction and offering resources for continuing education. The most recent information on best practices in language education is available to EFL teachers through AI-driven suggestions for instructional methods, evaluation procedures, and classroom management. AI-based analytics can also give teachers useful data on students' progress, enabling them to optimize learning outcomes and make informed pedagogical decisions. AI is transforming EFL instruction and has the potential to improve instructional efficacy, student engagement, and lesson design, according to Muhammadi *et al.* (2025). By using AI-driven technologies to provide more individualized, interactive, and culturally appropriate learning experiences, teachers can help EFL students acquire the language and communicate more effectively. AI technology will probably play a bigger part in language teaching as it develops further, offering even more creative solutions for EFL training that benefit both teachers and students.

According to Moundridou *et al.* (2024), artificial intelligence (AI) plays a revolutionary role in enabling diversified education, highlighting its importance as a crucial tool for teachers creating inquiry-based classes. Their study investigates how educators may create curricula that accommodate different student learning styles, aptitudes, and cognitive processing speeds using AI-powered technologies. With the help of AI-driven insights, educators can create individualized learning pathways that cater to the requirements of both advanced and difficult students, guaranteeing that everyone gets the perfect mix of support and challenge. Because varied instruction maximizes learning results in mixed-ability classes, this flexibility is extremely beneficial. STEM (science, technology, engineering, and mathematics) education benefits greatly from artificial intelligence. Moundridou *et al.* (2024) claim that by offering personalized learning paths, AI-powered platforms improve students' understanding of difficult mathematical and scientific ideas. With the help of these personalized learning pathways, which allow students to move at their own pace, top performers can complete challenging problem-solving activities while those who need more support can reinforce basic concepts. AI-based simulations, virtual labs, and interactive models further improve STEM education by offering hands-on experiences that link theoretical understanding with practical application. By enabling real-time assessment and feedback, AI also enables teachers to precisely monitor students' progress. To identify patterns and knowledge gaps, AI-powered examinations and quizzes analyze student responses. By using these tools, educators can rectify misconceptions before they become barriers to learning by adapting their teaching methods in response to real-time feedback. For example, if AI finds that a large portion of pupils have trouble understanding a mathematical theorem, it can suggest that a teacher study it with the help of interactive exercises, peer discussions, or visual aids. By providing data-driven insights into trends in student performance, AI-powered analytics assist teachers in improving their lesson plans beyond examinations. Teachers can compare learning paths across cohorts, track long-term development, and carry out focused interventions to enhance student learning outcomes. In STEM fields, where grasping fundamental ideas is necessary to address increasingly complex subjects, this degree of analysis is very beneficial.

According to Moundridou *et al.* (2024), the application of AI in education is growing, particularly in STEM fields where conceptual knowledge and problem-solving skills are essential. AI uses data-driven decision-making, adaptive training, and real-time feedback to enable teachers to design more effective, personalized, and inquiry-based learning experiences. Artificial Intelligence (AI) has the potential to revolutionize STEM education by providing educators with the tools they need to produce the next generation of problem solvers and creative thinkers.

Artificial intelligence (AI) has the potential to completely transform the teaching profession by automating course design, significantly reducing workloads, and reducing cognitive strain, claim Rougeaux and Sharp (2023). They found that administrative tasks, including class planning, worksheet creation, and assessment organization, take up a significant amount of teachers' time. Teachers lose time that could be spent on deeper lesson reflections, student interaction, or improving their teaching techniques because of these necessary but repeated duties, which can be psychologically and physically taxing. AI-powered solutions solve this problem by streamlining these procedures, freeing up teachers to concentrate more on developing close bonds with students and enhancing classroom dynamics.

In just a few minutes, curriculum-aligned and structured lesson plans can be generated using artificial intelligence (AI)-powered tools, improving student preparation may employ enormous databases of educational resources to provide relevant activities, information, and assessment techniques based on particular learning objectives and student needs. With the option to modify and customize them to fit their teaching philosophies, this automation gives educators access to excellent, pre-structured resources. Furthermore, AI-generated lesson templates eliminate curriculum delivery discrepancies by maintaining coherence and consistency across various instructional components.

AI is essential for resource production as well as lesson planning. Creating worksheets, tests, and other teaching materials that cater to different student skill levels and learning objectives typically takes teachers hours. AI-powered solutions speed up this process by producing personalized worksheets, differentiated exercises, and even gamified learning activities that boost student engagement. According to student performance statistics, AI can also alter the materials such that more challenging assignments are offered to advanced students, and more scaffolding is supplied to struggling students.

The benefits of AI in automating lesson planning, speeding up administrative work, and facilitating data-driven instructional decision-making are highlighted by Rougeaux and Sharp (2023). Teachers can focus more on professional development, individualized instruction, and student engagement by using AI to reduce the amount of time spent on tedious tasks. AI's use in education is anticipated to grow as it develops, further altering instructional strategies and improving student learning results.

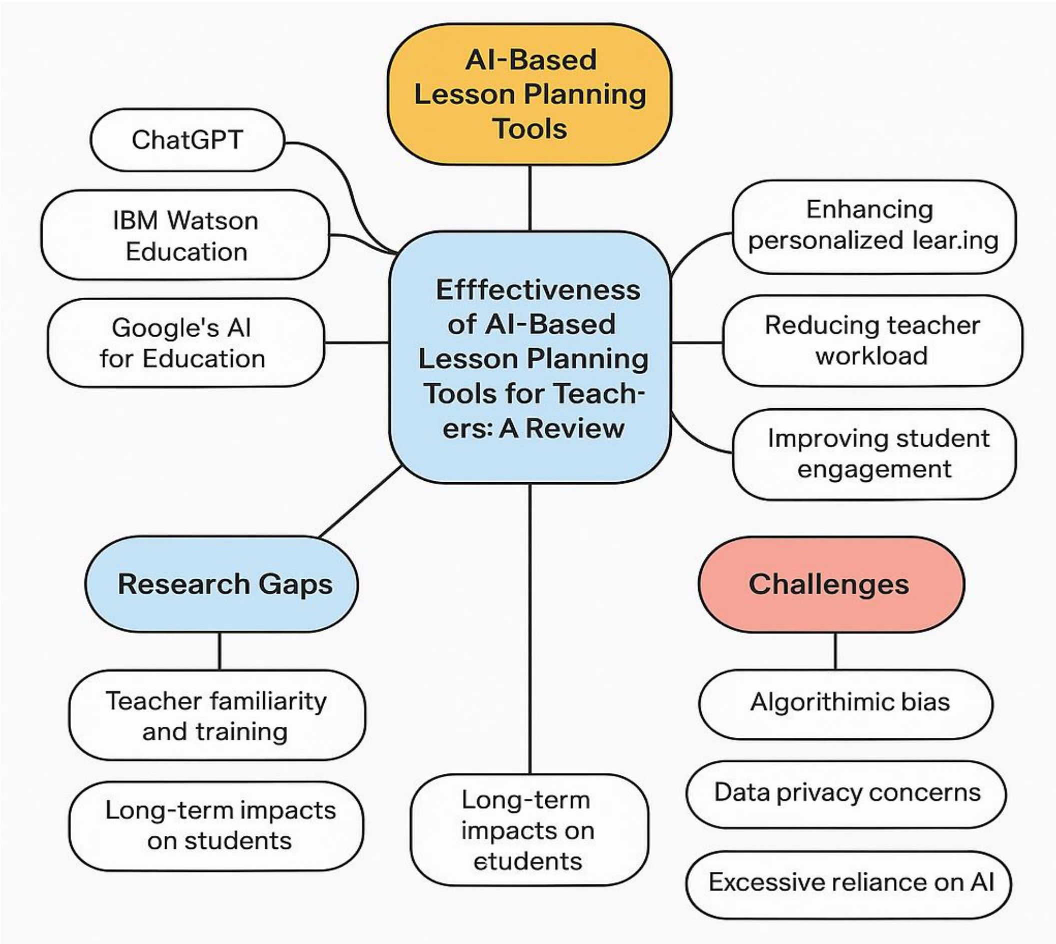

Table 2 gives educators and researchers a clear summary of the main advantages and difficulties of using AI-based technologies for lesson planning.

Table 2: Summary of Benefits and Challenges of AI-Based Lesson Planning Tools

Aspect	Benefits	Challenges
Instructional Quality	- Improves lesson clarity and coherence - Supports differentiated and personalized instruction	- May produce overly standardized plans -Lacks adaptation to emotional/personal classroom dynamics
Teacher Workload	- Reduces time spent on administrative tasks - Automates resource creation and lesson structuring	- Risk of overreliance, reducing teacher creativity
Student Engagement	- Creates dynamic, interactive lesson activities - Offers real-time feedback and adaptability	- Limited evidence on long-term impact on student creativity and inquiry-based learning
Professional Development	- Provides instant feedback for lesson improvement - Enhances reflective teaching practices	- Lack of AI literacy among many teachers - Need for specialized training programs
Ethical and Privacy Concerns	- AI can support inclusivity (e.g., supporting disabilities, multilingual learning)	- Risk of data privacy breaches - Algorithmic biases may reinforce inequalities
Cultural Adaptability	- AI suggests culturally relevant materials (in some platforms)	- Limited flexibility for diverse cultural, linguistic, and socio-economic contexts

Challenges and Research Gaps

- **Ethical and Data Privacy Issues:** A review of ethical concerns in assisting schools with AI has been published by Sandhu *et al.* (2024). While questions regarding data privacy and student security are often still unanswered in the AI infrastructure, AI developers have to begin protecting against data-related risks and violations of educational regulations to avoid any potential AI breaches and violations. To protect student privacy in a way that does not lead to algorithmic biases, the study points out the need for ethical guidelines as part of an effort to guide how AI is used in classrooms. On the data side, questions raised include whether or not instructors and students have access to information gathered by AI systems. Unprotected data might have a detrimental effect on students and their achievement when it generates biases.

- **Lack of Teacher Training & AI Literacy:** According to Kanvaria & Ritika (2024), limited use of AI tools is due to a lack of teacher training. Reportedly, while AI has the potential to improve lesson planning processes, many teachers don't have the technical capability to effectively use AI-assisted lesson planning tools in their classroom settings. Responsible professional development courses that address AI literacy are required, which will enable schools to provide teachers with confidence and complete functionality with AI-assisted lesson planning tools. Understanding machine learning models is typically required in the use of many AI tools; thus, the reason why teacher education programs should entail hands-on training workshops and integration of AI classes. The effectiveness of AI in lesson planning processes will remain severely limited without such activities.
- **Adaptability in Different Learning Settings** Chen *et al.* (2000) state that compared with the global state-of-the-art in education of AI, AI is "incomplete or non-adaptive" for various educational contexts. For example, students are not able to successfully use AI tools because they are typically created using a standardized programming language. To achieve inclusive development in AI education, further research should focus on creating models of AI that can adapt to different cultural, linguistic, and educational situations. AI lesson planning tools, for example, may not be enough to adequately support students with disabilities or those in low-resource environments with limited access to technology.
- **Overreliance on AI in Teaching Practices:** Another significant barrier to closing the gap is the concern that lesson preparation through AI-supported guidance could lead to a hyperreliant reliance on technology, in turn making teacher decision-making more dependent on technology. Occasionally, AI-generated lesson plans may lack the human component to address the emotional and psychological needs of students. To ensure that AI continues to function as a complement to rather than as a substitute for teachers' pedagogical skills, further research should address ways of finding a balance between teacher-driven lesson planning and artificial AI automation.

- **The impact of AI on student engagement and creativity:** Though AI may have positive effects on productivity, little is known about its effects on creativity and student engagement. Much has been made of research to examine whether the lesson plans mapped by AI encourage pupils to think critically and creatively or encourage strict and structured methods of teaching. How AI can be used to promote inquiry-based and interactive learning should be another topic of further research.
- **Ethical Implications of AI Decision-Making in Education:** A growing use of AI in lesson planning raises ethical questions about how AI can influence how lesson plans are organized, which instructional materials students are provided with, and who pays for it. Who is responsible for lesson plans that don't conform to the mandated academic standards? How can we as educators ensure the mission and values of a school are

represented in recommendations generated by AI? If we want AI to be used in education ethically, these are the things that need more work.

Conclusion:

There is a great deal of potential for AI-powered lesson planning software to improve the effectiveness of education and help teachers spend less time doing what they love. But there are significant research gaps that must be closed to achieve these goals. Specifically, the next generation of research should focus on the long-term effects of AI tools on the effectiveness of education and ensure that their use is configurable across multiple learning environments. Adoption of AI appropriately for education will require addressing problems relating to algorithmic bias, data privacy, and ethical considerations. Second, the potential of AI-powered lesson planning software is going to be maximized by increasing the number of instructor AI literacy programs. As researchers develop hybrid models involving AI and traditional teaching methods, they should also explore the effect of AI on student creativity and engagement.

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A BRIEF OVERVIEW OF ALGAL PIGMENTS: NATURE'S PALETTE AND BIOACTIVE TREASURE

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Introduction:

Algae are a group of primitive heterogenous autotropic thallophytes ranging from microscopic phytoplankton to macroscopic seaweeds. They are ubiquitous and occur in varied habitats such as freshwater, marine, on soil, on rock, as epiphytes or parasites on plants and animals, on hot springs, in deserts, snow covered areas etc. Most algae with polyphyletic origins, such as green, yellow-green, brown, and occasionally red algae, are classified as eukaryotes, while cyanobacteria are classified as prokaryotes. (Plaza *et al.* 2010). Their diverse pigment spectrum plays essential biological roles. These pigments possess significant bioactive properties with applications in food, agriculture, cosmetics, medicine, bioremediation, pharmaceuticals, and biotechnology. Moreover, 70 – 90 % of the oxygen in the atmosphere is produced by algae and form the first ring of the food chain in the marine ecosystem. Algae are the original source of fossil carbon found in crude oil and natural gas.

Algal Pigments

Pigments are one of the major criteria used in classifying different groups of algae. The major pigments present in algae are chlorophylls, carotenoids, and phycobiliproteins. Pigments are chemical compounds that reflect specific wavelengths of visible light, giving them their colour. Since each pigment absorbs only a narrow part of the spectrum, algae produce various coloured pigments to capture more of the sun's energy. Chlorophyll a is the primary pigment in all photosynthetic algae, with other types (b, c, d and e) also present. Carotenoids are orange or yellow pigments that function as accessory light-harvesting pigments and protect against photobleaching by scavenging reactive oxygen species. β-carotene plays a key protective role, while other carotenoids mainly assist in light harvesting. They also contribute to phototropism and phototaxis. Carotenoids are a class of pigments that include xanthophylls (e.g., fucoxanthin, lutein, and zeaxanthin), which give brown algae and diatoms their characteristic color, and carotenes (e.g., β-carotene), which contribute to the coloration of some green algae, brown algae and red algae. Phycobiliproteins (PBPs) are categorized into: Phycoerythrins (red), Phycocyanins (blue), Allophycocyanins. These pigments enhance light absorption and protect the photosynthetic machinery, allowing algae to thrive in various environments. Algal pigments have been used in food, medicinal, cosmetic, diagnostic, and pharmaceutical industries (Imchen and Singh, 2023). Algae are used in cosmetic and skin care products because of their superior photophysical qualities, high nutritional content, antioxidant nature, and antiaging components (Chakdar and Pabbi, 2017)

Currently, research on algal pigments is centered on exploring high-value bioactive compounds for applications in health and human services. There is a growing emphasis on substituting synthetic pigments with natural counterparts to avoid side effects when used for health applications. In contrast to their synthetic colors, natural algal pigments are a safe alternative for the human body and can even improve nutrition through a variety of biological processes. (Sun *et al.* 2023; Chakdar and Pabbi, 2017; Umashree *et al.,* 2023). Algal pigments are also proven to exert antioxidant, anti-carcinogenic, anti-inflammatory, anti-obesity, anti-angiogenic, and neuroprotective properties (Alotaiby, 2024). According to research, algal pigment can strengthen the immune system and may be linked to over 60 serious illnesses, including osteoarthritis, cancer, ischemic heart disease, and progeria. (Ambati *et al.,* 2019).

Microalgae are rich source of proteins, lipids, polysaccharides, minerals, vitamins, pigments, and polyunsaturated fatty acids, which have great trading and health value (Silva *et al.*, 2020). More than 600 naturally occurring carotenoid pigments are identified and characterized and among them Astaxanthin, β-carotene, and algal lutein are widely used in nutraceutical, pharmaceutical, cosmetic, food and animal feed industries (Zhang *et al.*, 2014). Microalgal species such as *Haematococcus pluvialis*, *Dunaliella salina*, *Chlorella* spp., *Scenedesmus* spp., *Spirulina platensis*, *Botryococcus braunii*, and various diatoms are well recognized for their ability to produce high-value carotenoids, including β-carotene, lutein, canthaxanthin, astaxanthin, and fucoxanthin. (Lamers *et al.*, 2008; Ranga Rao *et al.*, 2010; Zhang *et al.*, 2014; Shakeri *et al.*, 2018). Among the carotenoids, the red ketocarotenoid astaxanthin is considered the most valuable due to its strong pigmentation properties, potent antioxidant activity, and wide-ranging health benefits. It is also extensively used as a feed additive in aquaculture, particularly in salmon and lobster farming, where it imparts a characteristic red-orange coloration to fish and crustaceans. (Ambati *et al*, 2018; Liu *et al*, 2014).

Applications of Algal Pigments

Food Industry

A diverse range of eco-friendly, natural pigments derived from algae are widely utilized as colorants in the food industry (Chakdar and Pabbi, 2017). As reported by Sun *et al.* (2023), microalgae are currently recognized as a sustainable source to produce natural, food-grade colorants characterized by low allergenicity, toxicity, and carcinogenicity. In addition to serving as natural colorants, microalgal pigments also exhibit auxiliary preservative and antiseptic properties during food storage, owing to their inherent physiological activities. Chlorophylls are greenish pigments which are currently gaining immense attention as food, feed, cosmetic and pharmaceutical colorants and functional dietary supplements (Christaki *et al* 2.015). The pigments also are used in preservation and antisepsis in food storage. Chlorophylls were proven to serve as an excellent deodorant of foods (Carvalho *et al.* 2011). They are used as ingredient and colorant in beverages, fruit juices, pasta, diery products, sweeteners and soups. (Sun *et al.* 2023).

Carotenoids are red-orange pigments known for their antioxidative and preservative properties. They are commonly used to maintain the original color and flavor of food during storage and preservation, and are incorporated into products such as butter, margarine, dairy items, soft drinks, cakes, cooked sausages, confectioneries, nutraceuticals, baked and canned goods, as well as agricultural and aquaculture feeds (Rodriguez-Amaya, 2019, Sun *et al.* 2023, Borowitzka, 2013). β-Carotene also serves as a provitamin A source and is utilized to enhance the visual appeal of fish and crustaceans due to its vibrant coloration. Astaxanthin, a carotenoid extracted from *Haematococcus pluvialis*, is incorporated into human dietary supplements and salmonid feeds in countries such as Japan, the United States, and various European nations. Additionally, it is employed as a preservative in bread baking (Ohi *et al.* 2009).

Lutein is a yellow orange pigment commercially added to flavourings, tobacco, pastries, confectionery, infant formula and a variety of feed products to provide them with a distinctive and attractive color (Sun *et al.* 2023). Fucoxanthin a yellow brown pigment whose production and its application as a food colorant is limited. It can be applied to egg yolk, butter, pie, green tea cakes, baked foods and dairy products for a better color and functional role (Sun *et al.* 2022). Fucoxanthin improve stability and bioavailability of diary products. The red phycoerythrin is used as a colorant in confectioneries, syrups, dairy products, baked foods, gelatin desserts, dried foods, fermented milk products, ice cream and milk shakes (Dufossé *et al.*, 2005; Mishra *et al.*, 2008). Owing to its yellow fluorescence properties, it can be incorporated into cake decorations, soft drinks, and alcoholic beverages to impart fluorescent characteristics and enhance consumer appeal (Dufossé *et al.* 2005). The natural blue phyco cyanin pigment from cyanobacteria is being used to color ice cream, soft drinks, beverages, and yogurt in Japan. It can also be added in chewing gum, candies, popsicles, jellies, dairy products and soft drinks. (Mohammadi-Gouraji *et al.* 2019).

Pharmaceuticals and Nutraceuticals

Due to their potent bioactive properties, chlorophylls have been utilized as nutraceutical compounds and natural antioxidants. Additionally, they have demonstrated potential in modulating gut microbiota composition and reducing the risk of colorectal cancer. Given their ability to regenerate or functionally substitute for hemoglobin under deficiency conditions, chlorophyll supplementation has been proposed as an adjuvant therapy for managing thalassemia and anemia. (Marawaha *et al.*, 2004). Chlorophyll compounds are also suggested to have medicinal application with wound-healing, antimicrobial, anticancer, antimutagenic, antitumor and anti-inflammatory properties (Ferruzzi *et al.*, 2007; Pangestuti & Kim, 2011; Zepka *et al.*, 2019).

Due to antioxidative, anti-inflammatory and neuroprotective properties carotenoids can improve age-related macular degeneration and cardiac dysfunction. They can also suppress cholesterol synthesis. Vitamin A is a vital micronutrient recognized for its role in preventing cataracts, dermatological disorders, and night blindness, and is considered essential for maintaining overall human health. Beta-carotene is used as pro-vitamin A (retinol) in multi-vitamin preparations. It is an excellent hepatoprotective agent, a cosmetic or a multi-vitamin preparation additive, and as a functional food component (Chiu *et al.*, 2017). Vitamin A activity of beta carotene protect skin against sunburn. According to Cezare-Gomes *et al.* (2019), it exhibits a broad spectrum of therapeutic properties, including retinoprotective, dermoprotective, anti-inflammatory, antihypertensive, antitumor, and antidiabetic effects. It has also shown potential in mitigating insulin resistance, age-related macular degeneration, ultraviolet-induced skin cancer, and oral carcinomas. Astaxanthin, a potent antioxidant, effectively scavenges free radicals and quenches reactive oxygen species (ROS) (Patel *et al.*, 2022, Shah *et al.*, 2016).). It also exhibits anti-obesity properties, supporting its use in nutraceuticals, dietary supplements, cosmetics, pharmaceuticals, and healthcare applications. Additionally, oral formulations containing astaxanthin have been employed in the treatment of Helicobacter infections in the gastrointestinal tract. It also acts as hepatoprotector, anticancerogen and anti-aging compound (Rao *et al.*, 2013). It is also used in the treatment of neuronal damage, central nervous system injuries, heart disease, atherosclerosis, diabetes, cataracts, multiple sclerosis, chronic inflammatory disorders, cutaneous disorders and in functional foods (Sun *et al.* 2023, Sluijs *et al.*, 2015; Prasanna *et al.*, 2006; Sadiqqa *et al.*, 2024).

As a nutraceutical, lutein contributes to the management of macular degeneration, retinopathies, and cataracts, primarily through its ability to filter high-energy blue light, thereby protecting ocular tissues from its harmful effects. (Andrade *et al.*, 2014). It is also useful in the prevention of cardiovascular diseases, diabetes, atherosclerosis, alcohol-induced liver injury skeletal ischemia, some cancers and helps to strengthen immunity (D'Alessandro, 2016). Natural fucoxanthin from diatoms obtains a great potential for application on cosmetics, pharmaceuticals, food, poultry feed, and aquaculture industries, due to its unique bioactive structures and potent health benefits to humans. (Sun *et al.*, 2023). It has excellent antioxidant and ROS scavenger activity. Fucoxanthin exhibits anti-obesity, anti-inflammatory, and anticancer properties. It is an added ingredient in weight loss supplements. It helps to cure many chronic diseases such as type 2 diabetes, heart disease, high cholesterol, osteoporosis, hypertension, metabolic syndrome, liver disease, and some specified cancer such as skin, colon, prostate, liver cancers. (Sun *et al.,* 2023). Fucoxanthin derived from the microalga *Phaeodactylum tricornutum* has been found to improve its stability and bioavailability when added to dairy products (Cezare-Gomes *et al.,* 2019). Fucoxanthinol, extracted from diatom *Nitzschia laevis*, has neuroprotective action and hence used in food supplements and pharmaceutical products (Li *et al.,* 2020). Fucoxanthin helps to inhibit the growth of human leukemia cells and neuroblastoma cells. Phycobiliproteins possess cytotoxic, apoptosis, anti-alzhelmeric and antioxidant activity (Jacob-Lopes *et al.*, 2019; Sigurdson *et al.* 2017). Phycocyanin has immunomodulatory and neuroprotective effects. Ravi *et al.* (2015) demonstrated the anticancer therapeutic potential of phycocyanin against triple-negative breast cancer cells, while Liao *et al.* (2016) extended this research by evaluating its efficacy on human pancreatic adenocarcinoma through both in vitro and in vivo experiments.

Cosmetics and Skincare

Algae-derived secondary metabolites are widely recognized for their skin benefits, including protection from UV radiation and the prevention of rough texture, wrinkles, skin flaccidity, and premature aging due to their antioxidant properties. As a result, the use of bio compounds and algae extracts in cosmetic formulations is steadily increasing, offering safe and environmentally sourced materials for skincare (Maíra *et al.* 2017). Diverse algal species are now widely used in the treatment of various skin-related issues, serving as moisturizers, texture enhancers, sunscreens, and anti-wrinkling agents (Wang *et al.* 2015). Excess melanin production leads to skin pigmentation, which needs to be controlled. Pigments such as fucoxanthin, derived from brown algae like *Laminaria japonica*, *Alaria*, *Chorda*, and *Macrocystis*, have been shown to inhibit tyrosinase activity, thereby reducing melanin synthesis (Shimoda *et al.* 2010). These pigments contribute to skin whitening and also help in reducing skin wrinkles.

Carotene, particularly β-carotene present in green and red algae, exhibits potent antioxidant activity that contributes to skin rejuvenation, mitigates the effects of cutaneous aging, and enhances the skin’s protective mechanisms against oxidative stress. Furthermore, its application has been associated with a reduced risk of skin carcinogenesis (Keen and Hassan, 2016). Algal species such as *Turbinaria ornate*, *Ahnfeltiopsis*, *Colpomenia*, *Gracilaria*, *Halymenia*, *Hydroclathrus*, *Laurencia*, *Porphyra umbilicalis*, *Padina*, *Polysiphonia* are used as anti-aging agents (Kelman *et al.* 2012). Polysaccharides extracted from algal species such as *Saccharina japonica, Chondrus crispus,* and *Codium tomentosum* enhance moisture absorption and retention, exerting a soothing effect and promoting effective water circulation within the skin—crucial for maintaining hydration under hot and arid conditions (Wang *et al.,* 2013; Couteau and Coiffard, 2016). Antioxidants play a crucial role in promoting skin firmness, minimizing wrinkle formation, and reducing inflammation. Retinoic acid, a biologically active derivative of vitamin A produced by cyanobacteria, has been shown to diminish hyperpigmentation, including dark spots and dark circles, while also enhancing skin elasticity (Kelman *et al.* 2012).

Antioxidant-rich pigments such as astaxanthin, derived from *Haematococcus pluvialis*, are widely utilized in anti-aging formulations due to their potent free radical-scavenging properties. Additionally, the UV-protective capabilities of various algal pigments have enabled their incorporation into sunscreen formulations. These bioactive compounds also exhibit potential for use in dentifrice products and a variety of cosmetic applications targeting skin care (Sun *et al.* 2023). β-carotene, commonly included in multivitamin preparations, serves as a provitamin A (retinol) source and is employed in the formulation of both cosmetic products, such as sunscreens—and health-promoting foods. Similarly, lutein demonstrates photoprotective effects against ultraviolet (UV)-induced skin damage, supporting its application in topical skin care products, particularly sunscreens.

Among macroalgae, *Chondrus crispus* is a notable source of phycoerythrin, omega-3, and omega-6 fatty acids, which function as emollients with moisturizing and skin-soothing properties. These bioactive compounds also contribute to anti-inflammatory effects and aid in the nourishment and repair of dry or damaged hair. Similarly, green algae such as *Ulva lactuca* contain chlorophyll-a, chlorophyll-b, β-carotene, oleic acid, linoleic acid, and linolenic acid—compounds known for their antioxidant and anti-inflammatory activities. These constituents support skin elasticity, stimulate collagen synthesis, and exhibit anti-wrinkle, emollient, and moisturizing effects.

Brown algae species such as *Postelsia palmaeformis* and *Fucus vesiculosus* produce chlorophyll-c and fucoxanthin, which exhibit skin-softening, anti-wrinkle, nourishing, and moisturizing properties. These compounds also possess anti-inflammatory effects, contribute to skin tightening, and stimulate metabolic activity. Red algae, such as *Porphyra umbilicalis*, produce phycoerythrin and α-linolenic acid, which function as effective skin-conditioning agents. *Ascophyllum nodosum,* another brown alga, contains chlorophyll-c, fucoxanthin, and alginates, which collectively serve as anti-aging, anti-wrinkle, and smoothing agents (Surabhi *et al.* 2018).

Microalgae such as *Spirulina* are rich in phycocyanin and produce bioactive compounds like gamma-linolenic acid, phycocyanobilin, and phycoerythrobilin, which are utilized for their anti-aging, anti-wrinkle, collagen-synthesizing, anti-inflammatory, nourishing, and antioxidant properties (Hosseini *et al.* 2013). Fucoxanthin, myristic acid, oleic acid, and cantaxanthin, derived from brown algae species such as *Isochrysis*, function as antioxidants, sun-care agents, soothing agents, and anti-irritants. *Dunaliella salina*, known for its high β-carotene, palmitic acid, linolenic acid, and β-cryptoxanthin content, is employed for its antioxidant, smoothing, and anti-inflammatory effects (Widowati, 2017). *Chlorella vulgaris* contains β-carotene, palmitic acid, palmitoleic acid, and polysaccharides, which are incorporated into anti-aging formulations, as depigmentation agents, and for their moisturizing and thickening properties.

Fluorescent properties of phycobiliproteins are utilized in medical diagnostics and imaging techniques. Microalgal pigments are explored for use in biofuels and environmental monitoring.

Natural Dyes

Among natural dye sources, algal pigments have shown considerable promise; however, their application in the textile industry remains limited due to insufficient research on effective extraction and dyeing techniques (Azeem *et al.*, 2019). *Chlorella vulgaris*, known for its high chlorophyll content, has been identified as a promising source for producing natural green dyes (*Almoulki & Akkaya, 2023*). Diatoms are especially notable for their intricate silica shells and their ability to manipulate light, producing a range of vivid pigments that enhance their value as natural dye sources (Ayyanar *et al.*, 2023). Additionally, research on *Arthrospira (Spirulina) platensis* highlights the potential of phycocyanin, a blue pigment, as a natural textile dye (Ciptandi *et al.*, 2021). Notably, this pigment also shows potential in the cosmetic industry, particularly as a natural hair dye (Kraseasintra *et al.*, 2022).

Conclusion:

Algae-derived bioactive compounds, including pigments such as phycocyanin, fucoxanthin, β-carotene, and various fatty acids, offer a wealth of potential for skin care, anti-aging, and other cosmetic applications. These compounds exhibit antioxidant, anti-inflammatory, moisturizing, and skin-nourishing properties, making them invaluable in addressing a wide range of skin concerns. Algal pigments, serving as nature's vibrant palette, hold immense promise across diverse industries, particularly in cosmetics, food, and pharmaceuticals. To fully harness this potential, sustainable cultivation practices and optimized growth conditions must be prioritized to enhance pigment production. Moreover, proper regulatory frameworks are essential for ensuring safety and standardization across applications. With continued research and innovation in algal biotechnology, the commercialization of these pigments can contribute significantly to health, nutrition, and environmental sustainability. The future of algal pigments in scientific research and practical applications offers vast opportunities that could benefit humanity in numerous ways.

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PLASMA CATALYSIS - A SYNERGISTIC APPROACH FOR SUSTAINABLE CHEMICAL PROCESSES

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Abstract:

Plasma catalysis is an innovative and synergistic approach that combines non-thermal plasma (NTP) with heterogeneous catalysis to enable energy-efficient and selective chemical transformations. Operating under ambient or mild conditions, plasma catalysis offers unique advantages in activating stable molecules such as CO_2, CH_4, and N_2, making it highly relevant for applications in environmental remediation, energy conversion, and sustainable chemical synthesis. This chapter provides an in-depth overview of the principles of plasma catalysis, the interactions between plasma species and catalyst surfaces, reactor configurations, and key application areas including NO_x removal, CO_2 conversion, hydrogen production, and ammonia synthesis. Mechanistic insights, experimental challenges, and future perspectives for industrial implementation are also discussed. The integration of plasma technology with catalysis presents a transformative strategy for addressing global challenges in green chemistry and sustainable development.

Keywords: Plasma catalysis; Non-thermal plasma; Dielectric barrier discharge; CO_2 conversion; NO_x removal; Ammonia synthesis; Hydrogen production; Synergistic effects; Environmental catalysis; Sustainable chemistry

1. Introduction:

Plasma catalysis is an emerging interdisciplinary field that combines non-thermal plasma (NTP) technology with heterogeneous catalysis to facilitate and enhance chemical transformations. It has garnered significant attention for its potential in environmental remediation, energy conversion, and sustainable synthesis processes, particularly under mild operating conditions. Unlike traditional thermocatalysis, plasma catalysis offers rapid activation of molecules through energetic electrons, enabling reactions at lower temperatures and pressures. The synergy between plasma and catalyst surfaces opens new avenues for controlling reaction pathways, improving selectivity, and increasing energy efficiency.

2. Fundamentals of plasma catalysis

2.1 Non-thermal plasma

Non-thermal plasma is a partially ionized gas composed of electrons, ions, radicals, and neutral species. It is typically generated using electrical discharges such as dielectric barrier discharge (DBD), corona discharge, or microwave discharge. In NTP, the electron temperature (several eV) is much higher than that of the bulk gas, which remains near ambient temperatures. This condition enables selective excitation and dissociation of molecules without the need for bulk heating.

2.2 Plasma-catalyst interactions

The unique environment of plasma catalysis facilitates complex interactions:

- Surface activation: Plasma-generated species such as O, H, OH, or excited molecules can adsorb onto the catalyst surface and alter its reactivity.
- Electronic effects: Plasma can induce changes in the electronic structure of catalysts, such as modifying oxidation states or creating surface defects.
- Synergistic mechanisms: Plasma and catalysis together may yield reaction pathways not available through either approach alone (e.g., plasma-induced dissociation followed by surface-catalyzed recombination).

3. Reactor designs and configurations

Plasma catalysis systems are broadly classified into two types:

3.1 In-Plasma Catalysis (IPC)

In IPC systems, the catalyst is placed directly within the plasma discharge zone. This allows direct interaction between plasma species and the catalyst, enhancing synergy. However, catalyst degradation due to high-energy species may be a concern.

3.2 Post-Plasma Catalysis (PPC)

In PPC, the plasma zone is spatially separated from the catalyst. This configuration reduces catalyst damage and allows for separate optimization of plasma and catalytic conditions, although the synergy may be reduced compared to IPC.

Hybrid designs combining IPC and PPC elements are also being explored for performance optimization.

4. Applications of plasma catalysis

4.1 Environmental remediation

Plasma catalysis has been extensively studied for the abatement of pollutants such as NOx, VOCs, and CO:

- NOx removal: Plasma-assisted selective catalytic reduction (SCR) uses ammonia or hydrocarbons as reducing agents in the presence of catalysts such as Cu- or Fe-exchanged zeolites, achieving high NOx conversion at low temperatures (Mehta *et al.*, 2018).

- VOCs decomposition: Synergistic systems have demonstrated improved mineralization of VOCs like toluene and formaldehyde, with enhanced CO2 selectivity and reduced ozone formation (Zhou *et al.*, 2020).

4.2 CO_2 utilization

Plasma catalysis is an attractive approach for CO2 conversion to value-added products such as CO, CH4, or methanol under mild conditions. Catalyst materials like Ni, CeO2, or perovskites have shown enhanced activity and selectivity when combined with plasma discharge (Gao *et al.*, 2021).

4.3 Hydrogen production

Reforming of hydrocarbons and biomass-derived feedstocks using plasma catalysis enables efficient hydrogen production. Methane reforming, for example, benefits from reduced coking and improved H2/CO ratios with plasma-assisted systems (Wang *et al.*, 2019).

4.4 Ammonia synthesis

Ammonia synthesis under plasma catalysis can bypass the harsh conditions of the Haber–Bosch process. Recent studies using Ru- or Fe-based catalysts in DBD reactors have demonstrated promising ammonia yields at ambient pressure (Hong *et al.*, 2022).

5. Mechanistic insights

Understanding the underlying mechanisms in plasma catalysis remains a significant challenge due to the complexity of plasma chemistry and surface processes. However, several studies using in-situ diagnostics and kinetic modeling have provided insights:

- Optical Emission Spectroscopy (OES) and Mass Spectrometry (MS) are employed to detect transient species in the plasma phase.
- In situ DRIFTS and XPS help elucidate surface reactions and catalyst modifications.

These tools have revealed that plasma catalysis often involves a combination of gas-phase excitation and surface-mediated steps, which are difficult to decouple experimentally.

6. Challenges and future perspectives

Despite the growing interest, plasma catalysis faces several challenges:

- Energy efficiency: High energy input relative to product output remains a limiting factor.
- Scalability: Translating lab-scale setups to industrial applications requires robust reactor designs and process integration.
- Catalyst stability: Long-term operation under plasma conditions may degrade catalyst structure or activity.
- Mechanistic understanding: More advanced characterization and modeling techniques are needed to unravel reaction pathways.

Future research directions may include the development of tailored catalyst supports, AI-guided process optimization, and integration with renewable energy sources.

Conclusion:

Plasma catalysis presents a promising frontier in catalysis science by offering unique advantages for sustainable chemical processing. By combining the strengths of non-thermal plasma and heterogeneous catalysis, it enables new reaction pathways, improves process selectivity, and reduces energy consumption. Continued interdisciplinary efforts in materials science, plasma physics, and reactor engineering are essential to unlock its full potential for industrial deployment.

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SEPARATION OF HEAVY METAL IONS FROM INDUSTRIAL EFFLUENTS: A TECHNOLOGICAL APPROACH TO SUSTAINABLE ECONOMIC DEVELOPMENT

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Abstract:

This report critically evaluates five key strategies for treating heavy-metal-contaminated wastewaters—chemical precipitation, ion exchange, membrane filtration, adsorption, and electrochemical methods. It emphasizes the environmental risks posed by toxic metals like Pb^{2+}, Cd^{2+}, Cu^{2+}, Ni^{2+}, and Cr^{3+}, and outlines the strengths and limitations of each technique in terms of removal efficiency, cost, energy consumption, and recovery potential. The study highlights recent advancements, including biopolymer flocculants, high-selectivity resins, advanced membranes, nanomaterial-based adsorbents, and electrochemical recovery systems. It concludes that integrated hybrid approaches offer the most promising solutions for meeting regulatory requirements and supporting circular economy principles.

Keywords: Heavy Metal Remediation, Wastewater Treatment, Adsorption, Electrochemical Methods, Membrane Filtration

1. Introduction:

Water contamination by heavy metal ions—such as lead (Pb^{2+}), cadmium (Cd^{2+}), copper (Cu^{2+}), nickel (Ni^{2+}), and chromium (Cr^{3+})—poses severe environmental and public health risks due to their toxicity, persistence, and bioaccumulation potential. Chemical precipitation—using hydroxide or sulfide reagents—is one of the oldest and most widely applied removal methods, relying on pH adjustment to convert soluble metalsinto insoluble hydroxides or sulfides, followed by sedimentation or flotation [1,2]. Although simple and cost-effective, hydroxide precipitation produces large, amphoteric sludges that can re-dissolve under extreme pH [3], whereas sulfide precipitation yields denser, more stable precipitates with >99 % removal but requires careful handling due to H_2S toxicity [4]. Recent advances—such as real-time pH/reagent dosing, hybrid trains with membranes or adsorption polishing, and "green" biopolymer flocculants—have significantly reduced chemical usage and improved sludge dewaterability [5].

Ion exchange offers high selectivity and regenerability by exchanging aqueous metal ions with benign ions on resin matrices, with removal efficiencies often exceeding 95 % [6][7]. Both cation and anion exchange resins—synthetic (e.g., polystyrene-divinylbenzene) and natural (zeolites)—are employed, and captured metals can be eluted for recovery using acid or base washes [8]. Despite high capital and operating costs and the generation of concentrated brines[9], innovations in chelating resins and hybrid membrane-ion exchange systems have enhanced trace-level removal and environmental sustainability [10].

Membrane filtration, particularly ultrafiltration (UF) and reverse osmosis (RO), provides effective separation of suspended solids, macromolecules, and dissolved ions [11]. UF membranes (0.01–0.1 µm) remove over 98% of turbidity and more than 90% of metal–organic complexes, while RO membranes offer >99% rejection of dissolved salts and metals under high pressures [12]. However, membrane fouling—ranging from organic to biological—remains a major limitation, driving innovations in nanocomposite materials, dynamic membrane systems, and advanced pre-treatment processes [13-16].

Adsorption utilizes materials like activated carbon, biochar, clays, silicas, chitosan, and metal-organic frameworks to remove heavy metals through ion exchange, electrostatic attraction, and chelation [17,18,19]. Under optimal conditions, this method achieves over 95% removal efficiency [20,21]. Continuous treatment is enabled by fixed-bed columns with breakthrough monitoring, and cost-effectiveness is enhanced through bio-based adsorbents and efficient regeneration techniques [22,23].

Electrochemical treatments exploit electrical energy to remove or recover heavy metals with minimal reagent use [24,25]. Techniques include electrodeposition (achieving >99% plating efficiency), electrodialysis (ion concentration via selective membranes), capacitive deionization (ion adsorption in electrical double layers), and microbial electrochemical systems that integrate biofilms with electrodes for contaminant removal and potential energy generation [26]. These approaches offer high selectivity and align with sustainable recovery goals.

Collectively, these five separation strategies—chemical precipitation, ion exchange, membrane filtration, adsorption, and electrochemical techniques—offer a comprehensive toolkit for the effective remediation of heavy metal-laden wastewaters. The following sections will explore each method's principles, materials and process parameters, performance metrics, and practical considerations for large-scale implementation.

2. Chemical Precipitation

Chemical precipitation is one of the oldest and most commonly used methods for removing heavy metals from wastewater, relying on pH adjustment and the addition of reagents like lime ($Ca(OH)_2$) or sodium sulfide (Na_2S) to convert soluble metal ions into insoluble hydroxides or sulphides [1-4]. While hydroxide precipitation is simple and cost-effective, it generates large, unstable sludge that may re-dissolve under extreme pH. Sulfide precipitation offers higher efficiency and more stable precipitates but poses safety concerns due to H_2S

toxicity. Recent advancements, such as real-time dosing, hybrid systems, and eco-friendly flocculants, have improved efficiency and reduced environmental impact. Example Reaction: $M^{2+} + 2\ OH^- \rightarrow M(OH)_2$ (precipitate)

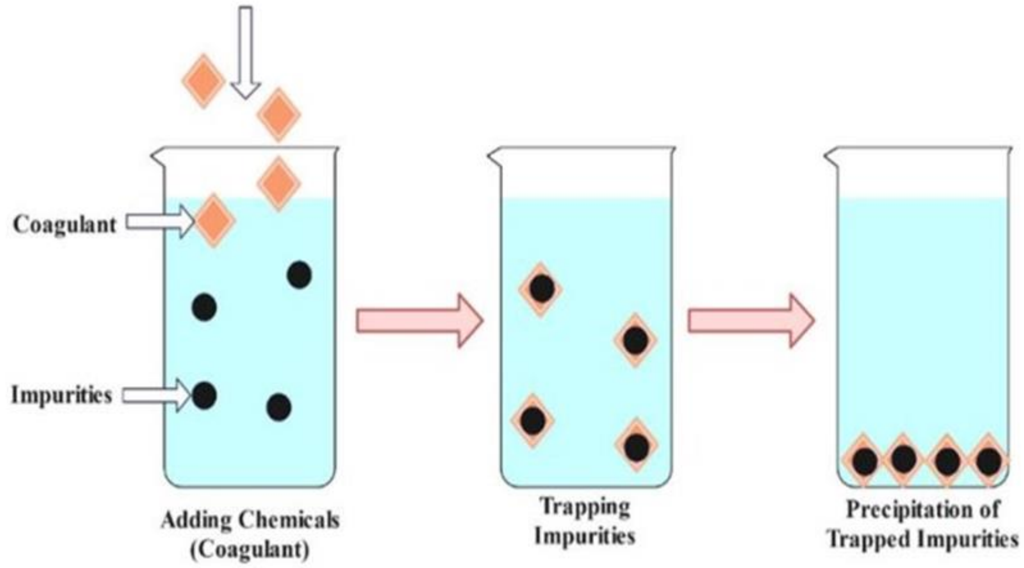

Fig. 1: Chemical precipitation process

2.1 Fundamental Principles

2.1.1 Reaction Chemistry:

Chemical precipitation involves converting dissolved heavy metal ions into insoluble compounds. In hydroxide precipitation, metal ions (M^{2+}) react with hydroxide ions to form metal hydroxides, with optimal pH ranges depending on the metal type. Sulfide precipitation forms metal sulfides, which are more stable and settleable, effective at reducing concentrations to µg/L levels using reagents like Na_2S, H_2S, or biogenic sulfides from sulfate-reducing bacteria.

2.1.2 Process Parameters:

Efficient precipitation relies on tightly controlled pH, appropriate reagent dosing (typically with a 5–15% excess), and optimized mixing and contact time to form settleable flocs. Elevated temperatures accelerate reaction rates, while high ionic strength may interfere with precipitation efficiency.

2.2 Types of Precipitants

2.2.1 Inorganic Hydroxides:

Common alkaline precipitants include lime, which is cost-effective and increases pH to ~12, and NaOH or soda ash, which offer precise pH control at higher cost. Lime also facilitates $CaCO_3$ co-precipitation to aid floc formation.

2.2.2 Sulfide Reagents:

Direct sulfide dosing with Na_2S or H_2S ensures effective metal removal but raises toxicity and odor concerns. Alternatively, biogenic sulfides from microbial processes offer safer, sustainable in-situ precipitation.

2.2.3 Specialty & Hybrid Precipitants:

Ferrite co-precipitation using iron salts produces well-settling metal-ferrite complexes. Organic precipitants like dithiocarbamates and xanthates create dense, filterable metal complexes, enhancing sludge characteristics.

2.3 Sludge Separation and Handling

2.3.1 Solid–Liquid Separation:

Hydroxide sludges are separated using clarifiers or lamella settlers, while lighter sulfide sludges require dissolved air flotation (DAF) systems to ensure efficient removal.

2.3.2 Dewatering & Disposal:

Post-separation, sludge is dewatered using belt presses, vacuum filters, or centrifuges to minimize volume. Metal-rich sludge can be processed for resource recovery through smelting or electrochemical extraction, supporting circular economy goals.

3. Ion exchange

Ion exchange is a selective, regenerable method for removing heavy metals from wastewater using synthetic or natural resins that exchange metal ions with benign ions on a solid matrix [6,7]. It achieves >95% removal efficiency and allows for metal recovery through acid/base regeneration [8]. While offering consistent performance with minimal chemical input, it faces challenges like high costs, pH sensitivity, and brine disposal [9]. Recent advancements include chelating and bio-based resins, as well as hybrid systems combining ion exchange with membranes or adsorption to enhance sustainability and efficiency [10].

3.1 Principles of Ion Exchange

Mechanism: Metal ions (e.g., M^{2+}) are exchanged with benign ions (e.g., Na^{+}) on resin sites, such as sulfonated groups in strong acid cation (SAC) resins.

Resin Types:

- SAC Resins: General heavy-metal removal.
- WAC Resins: Target divalent metals at higher pH.
- SBA Resins: Remove oxyanions like CrO_4^{2-}.
- Chelating Resins: High selectivity using ligands (e.g., iminodiacetate).

3.2 Process Design and Operation

Bed Configuration: Fixed-bed columns with staged operation (lead, regeneration, rinse) operate at 1–10 BV/h for efficient mass transfer.

Key Parameters:

- pH: Optimal range (e.g., 4–6) is critical.
- Competing Ions: Ca^{2+}, Mg^{2+} interfere; mitigated by selective resins.
- Temperature: Improves kinetics but may reduce resin life.

Regeneration & Recovery: Strong acid/base regenerants (1–4 M HCl or NaOH) elute metals; recovered regenerants can be reused, supporting sustainability.

3.3 Performance and Applications

Ion exchange removes 95–99% of metals like Pb^{2+}, Cu^{2+}, and Cd^{2+} from waters with 5–100 mg/L metal concentrations. Chelating resins polish down to ppb levels.

Applications include:

- Electroplating rinsewater recycling (Ni^{2+}, Cu^{2+}),
- Acid mine drainage (Fe^{3+}, Al^{3+}),
- Drinking water softening (Ca^{2+}, Mg^{2+}).

3.4 Advantages and Limitations

Aspect	Advantages	Limitations
Selectivity	Tailorable resin chemistries for specific metals	Competing ions reduce capacity
Regenerability	Multiple cycles; regenerant can be reused	Generates concentrated brine requiring disposal
Chemical Usage	Minimal chemical addition in treatment phase	High acid/base consumption during regeneration
Consistency	Stable, predictable removal performance	Resin fouling by organics/colloids; backwash needed
Scalability	Modular column design for any flow rate	High capital cost for large resin volumes

4. Membrane Filtration (Reverse Osmosis and Ultrafiltration)

Membrane filtration—primarily ultrafiltration (UF) and reverse osmosis (RO)—is widely used for removing suspended solids and dissolved metals from wastewater. UF membranes (0.01–0.1 µm) achieve >98% turbidity removal and >90% rejection of metal–organic complexes, while RO membranes, operated under 10–80 bar pressure, remove >99% of dissolved salts and metal ions. A key limitation is membrane fouling, which can cut flux by up to 50%. Advances such as nanocomposite materials, dynamic systems, and hybrid pre-treatment methods have significantly enhanced fouling resistance and removal efficiency for metals like Cu^{2+}, CrO_4^{2-}, and Pb^{2+}.

4.1 Principles of Membrane Filtration

4.1.1 Ultrafiltration (UF)

Ultrafiltration (UF) uses semipermeable membranes with pore sizes of 0.01–0.1 µm to remove suspended solids, macromolecules, microorganisms, and metal–organic complexes from wastewater at low pressures (0.1–2 bar). It achieves >98% turbidity removal and, when combined with complexing agents like carboxymethyl cellulose (complexation-UF), can reject >95% of heavy metals such as Cu, Ni, and Cr.

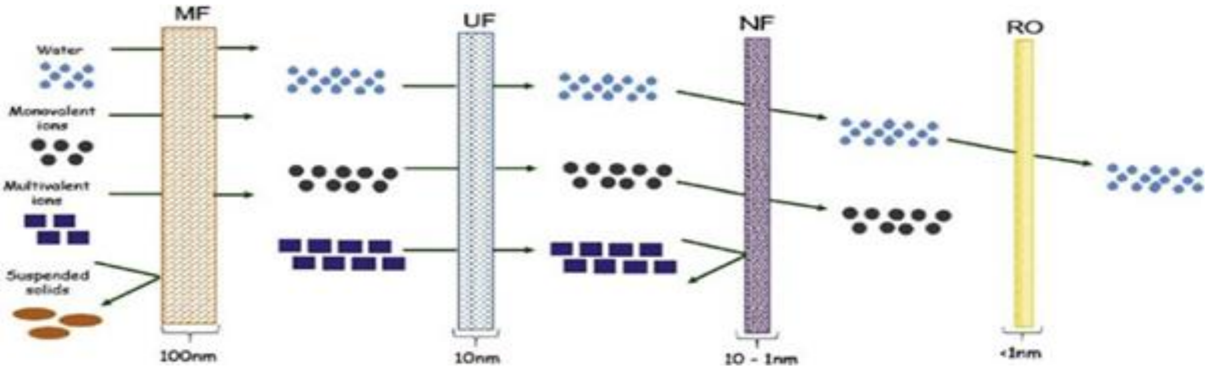

Fig. 2: Types of membrane filtration MF: microfiltration; UF ultrafiltration; NF: nanofiltration; RO: reverse osmosis.

4.1.2 Reverse Osmosis (RO)

Reverse Osmosis (RO) is a water purification process where pressure is applied to force water through a semipermeable membrane, removing salts, bacteria, and other contaminants. RO membranes, typically made of polyamide or cellulose, operate at high pressures (10–80 bar) and achieve over 99% rejection of salts and metals (e.g., 99.8% for Pb^{2+}, Cd^{2+}) [12]. Although highly effective, RO results in lower permeate flux (10–30 $L/m^2{\cdot}h$) compared to ultrafiltration (UF).

4.2 System Design and Operation Module Configurations:

Ultrafiltration (UF) uses hollow-fiber modules for high packing density and flat-sheet modules for easier cleaning and less fouling. Reverse osmosis (RO) employs spiral-wound modules to balance surface area and pressure drop, and tubular modules are used for high-fouling feeds.

Operating Parameters: UF operates at transmembrane pressures (TMP) of 0.1–2 bar, and RO at 10–80 bar. Higher TMP increases flux until reaching limiting flux due to concentration polarization [11]. High cross-flow velocity (0.5–2 m/s) reduces foulant deposition. Recovery rates are 80–95% for UF and 30–50% for RO to limit scaling.

4.3 Performance for Heavy-Metal Removal Ultrafiltration (UF):

UF alone achieves limited metal ion removal (<30–50%), but with complexation or precipitation pretreatments, rejection can exceed 90% [11].

Reverse Osmosis (RO): RO effectively rejects >99% of heavy metals, reducing concentrations to below 0.01 mg/L [12].

4.4 Membrane Fouling and Mitigation Fouling Mechanisms:

Fouling includes colloidal fouling (cake formation), organic fouling (gel-layer formation from NOM), scaling (salt precipitation), and biofouling (microbial growth and biofilm formation) [13].

Mitigation Strategies: Pre-treatment (coagulation/flocculation), membrane surface modification (e.g., TiO_2 nanoparticles), hydrodynamic control (backwashing), and chemical cleaning (acid/alkali) help reduce fouling [15].

4.5 Recent Innovations Nanocomposite Membranes:

Membranes embedded with graphene oxide or carbon nanotubes improve selectivity, permeability, and fouling resistance.

Dynamic Membrane Systems: Self-forming cake layers act as secondary membranes for fine polishing and fouling protection.

Polymer-Enhanced Ultrafiltration (PEUF): Water-soluble polymers improve metal rejection by complexing with metals.

Integrated Treatment Trains: Combining UF-RO with advanced oxidation processes (AOPs) or ion-exchange polishing supports zero liquid discharge (ZLD) [14].

6. Coagulation–Flocculation

Coagulation–flocculation is a key physico-chemical treatment for removing suspended solids, colloids, and dissolved contaminants, including heavy metals. Coagulation uses metal salts or electrocoagulation to destabilize particles, while flocculation promotes aggregation into larger, separable flocs using polymers or natural biopolymers. This dual process achieves high turbidity removal (>99%) and heavy metal removal (80–95%). Common coagulants include aluminum sulfate and ferric chloride, and flocculants like polyacrylamide and chitosan. Recent innovations focus on hybrid coagulants, biodegradable flocculants, and green alternatives like electrocoagulation [19].

5.1 Fundamentals of Coagulation–Flocculation Coagulation Mechanisms:

Coagulation neutralizes the electric double-layer repulsion of colloidal particles using coagulant ions (e.g., Al^{3+}, Fe^{3+}), allowing aggregation through van der Waals forces [16]. Metal salt coagulants, such as alum and ferric chloride, hydrolyze to produce metal hydroxides, which aid particle aggregation. Electrocoagulation uses anodic dissolution to generate coagulants in situ, improving dewatering properties.

Flocculation Dynamics: Flocculation involves gentle stirring to encourage particle collisions and aggregation. Synthetic polyelectrolytes, like polyacrylamide, or natural polymers, like chitosan, are used for bridging particles.

5.2 Process Design and Key Parameters Coagulant Selection and Dose:

Inorganic salts, like alum and ferric chloride, are effective but produce voluminous sludge, while pre-hydrolyzed coagulants (e.g., PAC, PFS) offer faster floc formation with less sludge. Electrocoagulation eliminates the need for chemical transport, with coagulant dose controlled by current density.

pH and Mixing: Optimal pH ranges for alum (6–7) and ferric salts (4–6) ensure efficient removal, with rapid mixing dispersing coagulants and slow mixing promoting floc growth [17].

Flocculant Type and Dose: Synthetic polyacrylamides and natural polymers like chitosan provide effective flocculation, with natural alternatives offering eco-friendly options [18].

5.3 Performance Metrics and Heavy-Metal Removal Turbidity and Solids:

Coagulation–flocculation can remove over 95% of turbidity, with denser PAC sludges being more easily dewatered than alum sludges [17].

Heavy-Metal Ion Removal: The process removes heavy metals by adsorption and co-precipitation with metal hydroxides, achieving 80–95% removal for metals like Pb^{2+}, Cd^{2+}, and Cr^{3+}. Optimizing flocculation time and polyelectrolyte dosing can boost removal efficiency to >98%.

5.4 Advantages and Limitations

Aspect	Advantages	Limitations
Efficiency	High turbidity & metal removal	Sensitive to pH and water chemistry
Cost	Low chemical cost; simple design	Sludge disposal; polymer costs
Sludge Characteristics	Dense PAC sludges; EC yields filterable flocs	Voluminous alum sludge; water content
Environmental Impact	Biodegradable flocculants	Aluminum residuals in treated water

6. Adsorption

Adsorption is an effective, cost-efficient method for removing heavy metal ions (e.g., Pb^{2+}, Cd^{2+}, Cu^{2+}, Ni^{2+}, Cr^{3+}) from wastewater by binding them onto solid adsorbent surfaces. Various materials, such as activated carbons, biochars, clays, and functionalized silicas, are commonly used to enhance capacity and selectivity [20]. Adsorption operates under ambient conditions, requires minimal chemical input, and can achieve over 95% metal removal when optimized. Key factors influencing performance include kinetics, pH, competing ions, and adsorbent regeneration [21]. Recent innovations focus on sustainable bio-derived adsorbents, nanoparticle-enhanced composites, and continuous systems for real-time monitoring [22].

Example Adsorption:

The surface-complexation (adsorption) step can be written generically as:

$$M^{2+}\,(aq) + \equiv S \rightarrow \equiv S–M^{2+}$$

where

- M^{2+} (aq) is the dissolved metal ion,
- $\equiv S$ represents an available adsorption site on the solid surface, and $\equiv S-M2+$is the metal bound to that site

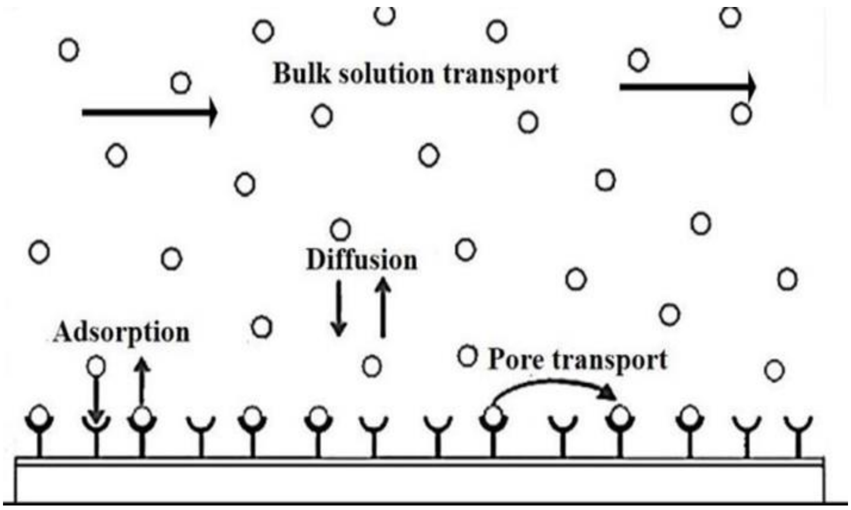

Fig. 3: Schematic of Adsorption process

6.1.1 Isotherms & Kinetics

Isotherm models, such as Langmuir and Freundlich, describe adsorption capacity and surface heterogeneity. Langmuir represents monolayer adsorption, while Freundlich accounts for multilayer adsorption. Kinetic models, including pseudo-first and second-order, help determine rate-limiting steps, like film diffusion or chemisorption, impacting metal uptake.

6.2 Adsorbent Types

- Carbon-based: Activated carbon (AC) offers high surface area (>1000 m^2/g) for versatile metal removal through physisorption and chemisorption. Biochar, derived from biomass pyrolysis, is cost-effective with tunable surface properties.
- Natural Minerals: Clays and zeolites have cation-exchange sites that work well for Pb^{2+} and Cu^{2+}. Iron-oxide nanoparticles like goethite and magnetite are effective for arsenic and chromium removal.
- Biopolymers: Chitosan, rich in amino groups, offers chelation sites, and cellulose-based hydrogels, functionalized with thiol or carboxyl groups, enhance metal binding.
- Synthetic & Advanced: Functionalized silicas and metal-organic frameworks (MOFs) provide high selectivity and capacity but face scalability challenges.

6.3 Operation

- Batch vs. Continuous: Batch systems are used for lab evaluations to optimize adsorbent dose, contact time, pH, and temperature. Fixed-bed columns are preferred for large-scale operations, with breakthrough curves used to monitor regeneration.
- Key Parameters: pH is often controlled between 5–7, as extreme pH levels reduce adsorbent efficiency. Contact time and dosage influence equilibrium, while competing ions (e.g., alkaline earth metals) can lower binding capacity.

- Regeneration: Metals can be desorbed using acidic (HCl), chelating (EDTA), or salt solutions (NaCl), with cycle stability varying by adsorbent; high-performance adsorbents can retain over 80% of their capacity for at least 5 cycles.

6.4 Performance Metrics

6.4.1 Removal Efficiency & Capacity

Activated carbon demonstrates high metal removal efficiency, typically achieving 80–95% under optimized conditions. Its adsorption capacity ranges between 50–300 mg of metal per gram of adsorbent, depending on the metal ion and operating conditions.

Biochar exhibits variable adsorption capacity (20–200 mg/g), largely influenced by the biomass feedstock and the method of thermal activation or chemical modification applied during its preparation [20].

Chitosan-based adsorbents show strong performance, with capacities between 100–250 mg/g for metals like Pb^{2+} and Cd^{2+}. Functionalization, such as grafting with specific ligands, further enhances metal selectivity and overall uptake efficiency.

6.4.2 Selectivity

The selectivity of adsorbents is primarily governed by their surface functional groups. Thiol-modified silicas display exceptional affinity for soft metal ions like Hg^{2+} and Ag^{+} due to strong thiol-metal interactions. In contrast, amine-rich materials preferentially bind transition metals such as Cu^{2+} and Ni^{2+}, making them suitable for targeted separation in mixed-metal waste streams.

6.5 Advantages and Limitations

Aspect	Advantages	Limitations
Efficiency	High removal (>95 %)	Lower for metal–organic complexes without pre-treatment
Simplicity	Ambient conditions; simple equipment	Requires pH adjustment, regenerants
Cost	Low for waste-derived adsorbents	High for engineered materials
Regeneration	Multiple reuse cycles	Capacity decline over cycles
Scalability	Fixed-bed columns scalable	Channelling and clogging risks

7. Electrochemical Methods

Electrochemical methods are efficient, reagent-free techniques for removing and recovering heavy metal ions from wastewater, using electrical energy to drive redox reactions, ion migration, and adsorption. Techniques include electrodeposition (for metal plating), electrodialysis (ion separation), electro-adsorption (capacitive deionization), and microbial electrochemical systems (using biofilms to remove contaminants). These methods reduce secondary waste and allow precise control, although challenges like energy consumption and electrode fouling remain. Recent advancements include AC electrodeposition, hybrid systems, and novel electrode materials like graphene [24-27].

7.1 Fundamental Principles of Electrochemical Metal Removal

Electrochemical processes use an external power source to drive reactions at electrodes or ion-exchange membranes. Metal ions undergo reduction or migration to oppositely charged electrodes. Performance depends on electrode material, cell configuration, applied voltage, and solution conditions (pH, conductivity, competing ions).

7.2 Electrodeposition

- Mechanism: Metal cations are reduced at the cathode to form a solid metal layer with >99% efficiency.
- Process Parameters: Current density, electrode materials (e.g., graphite, graphene oxide), and reactor configurations (flow-through or batch) affect performance.
- Applications: Used for metal recovery from electroplating rinse waters, supporting zero-liquid-discharge goals.

7.3 Electrodialysis (ED)

- Working Principle: Ion-exchange membranes separate cations and anions under an electric field, concentrating metals in specific streams.
- Operational Features: Membrane properties (capacity, thickness), cell design, and operating conditions (voltage, flow rate) impact recovery efficiency.
- Advantages: High selectivity, continuous operation, and low chemical usage, suitable for treating acid mine drainage and recovering metals like Zn^{2+} and Cu^{2+}.

7.4 Electro-adsorption (CDI)

- Principle: Ions accumulate in the electrical double layers of porous carbon electrodes and are desorbed during polarity reversal.
- Parameters: Electrode material (e.g., high-surface-area carbon), voltage window (1.0–1.2 V), and cycle times are key for optimal performance.
- Performance: Capacitive removal of divalent ions (e.g., Pb^{2+}, Cd^{2+}) can reach 80–90% efficiency with low energy consumption (0.5–1.5 Wh/g).

7.5 Microbial Electrochemical Technologies (METs)

- Concept: METs, such as microbial fuel cells, use electroactive microbes to catalyze redox reactions, reducing metals while generating electricity.
- Applications: Biocathodes reduce Cr(VI) and U(VI), while bioanodes oxidize organic substrates to supply electrons for metal reduction.
- Advantages & Challenges: These systems offer low chemical input and energy neutrality, but face slow kinetics, biofouling, and microbial complexity.

7.6 Hybrid & Emerging Approaches

- Bipolar/AC Electrodeposition: Alternating current helps prevent dendrite formation and allows ultra-trace metal removal (< µg/L).
- Combined ED-CDI Systems: Integration of electrodialysis and capacitive deionization enables high-purity metal recovery with minimal brine production.
- Smart Process Control: AI-driven sensors optimize energy usage and reduce fouling through dynamic adjustments.
- Novel Electrode Materials: Materials like graphene oxide and metal-organic frameworks improve selectivity, durability, and performance.

8. Summary Table of Methods

Method	Principle Removal	Efficiency	Operational Cost & Complexity	Limitations
Chemical Precipitation	Conversion of soluble metals to insoluble hydroxides/sulfides by pH adjustment and reagent addition	80–99 % (metal-dependent)	Low reagent cost; simple equipment; moderate chemical consumption	Large sludge volumes; sludge disposal; pH-sensitive
Ion Exchange	Exchange of aqueous metal ions with functional groups on resin beads; regenerable	95–99 % (often >99 % for targeted ions)	High resin and regeneration cost; requires periodic acid/base regeneration	Sensitive to competing ions; brine disposal; capital-intensive
Membrane Filtration	Size/charge-based separation via porous UF or dense RO membranes under pressure	UF: >98 % turbidity; RO: >99 % ions	High energy (especially RO); membrane modules; pre-treatment required	Fouling (colloidal, organic, scaling); high pressure demands
Adsorption	Binding of metals onto solid surfaces via ion exchange, electrostatic attraction, or chelation	>95 % Under optimized conditions	Moderate cost; simple columns; regenerant chemicals; adsorbent replacement	Adsorbent saturation; regeneration efficiency; kinetics dependent
Electrochemical Methods	Electrical driving of Redox (electrodeposition), Migration (electrodialysis), and adsorption (CDI)	>99 % for plating; 80–90 % CDI	Moderate to high energy; electrode materials; stack maintenance	Electrode fouling; energy consumption; scale-up challenges

9. Observations

Chemical precipitation is a low-cost method for heavy metal removal but is limited by moderate efficiency and high sludge production. In contrast, ion exchange and electrochemical techniques support metal recovery and align with circular economy goals, though they require more complex operations. Membrane and electrochemical systems offer high performance but are prone to fouling and demand advanced controls. Simpler methods like adsorption and precipitation lack selectivity and often produce non-reusable waste. Hybrid systems—such as combining precipitation with ultrafiltration or integrating ion exchange with membranes—offer more efficient, scalable solutions for diverse industrial wastewater treatments.

Conclusion:

In conclusion, addressing heavy metal contamination in industrial effluents requires the adoption of effective and sustainable separation technologies. While individual methods like adsorption, ion exchange, membrane filtration, and chemical precipitation offer specific advantages, hybrid approaches often deliver better efficiency and cost-effectiveness. Emphasizing metal recovery aligns with circular economy goals, turning waste into valuable resources. To support sustainable development, industries must prioritize eco-friendly, energy-efficient innovations that comply with environmental regulations. Overall, integrated metal separation strategies are essential for pollution control, resource conservation, and a cleaner industrial future.

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CATALYTIC REACTIONS IN CHEMICAL SYNTHESIS

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Abstract:

Catalytic reactions are central to modern chemical synthesis, offering an efficient and sustainable approach to the production of a wide array of chemicals, pharmaceuticals, and materials. Unlike traditional methods that may involve harsh conditions, toxic reagents, or high energy inputs, catalytic processes enable selective transformations under mild conditions with reduced environmental impact. Catalysts, by lowering the activation energy of reactions, enhance reaction rates and often enable the use of renewable feedstocks, contributing to greener and more sustainable industrial practices. The importance of catalytic reactions extends across various fields, from the synthesis of fine chemicals and bio-based products to energy-efficient processes like hydrogen production and CO_2 conversion. With continuous advancements in catalyst design, such as nanocatalysis, biocatalysis, and the development of highly selective catalysts, catalysis plays a crucial role in the future of chemical synthesis, providing solutions to both economic and environmental challenges.

Keywords: Chemical Synthesis, Catalysis, Chemical Synthesis, Sustainable Chemistry, Green Chemistry, Catalyst Deactivation, Nanocatalysis, Waste Reduction, Industrial Applications.

1. Introduction:

A catalytic reaction is a chemical process in which a catalyst speeds up the reaction rate without being consumed in the process. Catalysts achieve this by lowering the activation energy required for the reaction to occur. This allows reactions to take place more efficiently or at lower temperatures than they would otherwise. Catalytic reactions can be heterogeneous or homogeneous:

An example of a catalytic reaction is the Haber process, where nitrogen and hydrogen react to form ammonia, with an iron catalyst speeding up the process. In the Haber process, an iron (Fe) is used to accelerate the reaction at relatively lower temperatures (400–500°C) and pressures (150–300 atm). The iron catalyst provides a surface where nitrogen and hydrogen molecules can adsorb, breaking their strong bonds. This allows the atoms to rearrange and form ammonia more efficiently than they would without the catalyst (Gupta *et al.*, 2021). The Haber process is crucial for producing fertilizers that support global food production, as ammonia is a key ingredient in synthetic fertilizers.

2. Catalyst Materials:

Catalyst is a substance that increases the rate of a chemical reaction without itself being consumed or permanently altered during the reaction. The material of the catalyst plays a crucial role in its effectiveness, as it must have specific properties that allow it to facilitate the reaction. Catalysts can be classified into two main categories based on their physical state:

2.1 Heterogeneous Catalysts: These catalysts are in a different phase (solid, liquid, or gas) from the reactants. Solid catalysts are most common, especially in industrial processes (Sheldon and R. A., 2016). They work by providing a surface for the reaction to take place, allowing reactants to adsorb onto the catalyst surface, interact, and then desorb as products.

Examples	Use
Platinum (Pt)	in automotive catalytic converters to reduce harmful gases (CO, NO_x, and hydrocarbons).
Nickel (Ni)	hydrogenation reactions (e.g., converting unsaturated fats into saturated fats).
Alumina (Al_2O_3)	as a support for catalysts in processes like cracking in petroleum refining

2.2 Homogeneous Catalysts: These catalysts are in the same phase as the reactants (usually liquids). They often involve the formation of an intermediate complex with the reactants.

Example materials:

Transition metal complexes: These are often used in organic reactions, such as in the catalysis of hydrogenation by Rhodium or Palladium complexes.

Acids or bases: For example, sulfuric acid (H_2SO_4) or sodium hydroxide (NaOH) can be used to catalyze reactions like esterification or hydrolysis(Peter Munnik *et al.*, 2015).

2.3 Biocatalysts (Enzymes): These are biological molecules, typically proteins, that act as catalysts in biochemical reactions.Enzymes are highly specific and efficient, often working at mild conditions (e.g., body temperature and neutral pH).

Example materials:

2.3.1 Amylase: Catalyzes the breakdown of starch into sugars.

2.3.2 Lipase: Catalyzes the hydrolysis of lipids (fats).

2.3.3 Catalase: Breaks down hydrogen peroxide into water and oxygen.

2.4 Special Catalyst Materials:

2.4.1 Nanocatalysts: Nanomaterials, such as Gold nanoparticles, have shown unique catalytic properties due to their small size and high surface-to-volume ratio (Chaoliang Tan and Hua Zhang 2015).

2.4.2 Biomimetic Catalysts: These catalysts mimic the behavior of enzymes and are designed to replicate biological catalytic processes in synthetic reactions.

3. Catalyst Deactivation:

It refers to the loss of catalytic activity over time, which can lead to a decrease in the efficiency of the catalytic process. Deactivation can occur due to several factors, including physical, chemical, and mechanical changes to the catalyst. The deactivation process can vary depending on the type of catalyst and the reaction conditions.

3.1 Common Causes of Catalyst Deactivation:

3.1.1 Fouling: It occurs when unwanted materials, often solid or liquid, deposit on the surface of the catalyst, blocking the active sites where the reaction occurs. This reduces the surface area available for reactants to interact with the catalyst. In industrial reactions like catalytic cracking or reforming, hydrocarbons or coke (carbon deposits) can build up on the catalyst, leading to a reduction in catalytic activity.

3.1.2 Poisoning: It happens when a substance (called a poison) binds irreversibly to the catalyst's active sites, preventing reactants from interacting with those sites. Poisons are often impurities in the feed or reaction products. In catalytic converters, substances like sulfur compounds (e.g., sulfur dioxide, SO_2) can poison the platinum or palladium catalyst, reducing its ability to convert harmful gases.

3.1.3 Sintering: occurs when the catalyst particles agglomerate and grow larger, often due to high temperatures. This reduces the surface area of the catalyst, decreasing its efficiency. In reactions that occur at elevated temperatures, metals like platinum can form larger particles, which are less effective at catalyzing reactions (Li *et al.,* 2020).

3.1.4 Coking: It involves the formation of carbon-rich deposits (coke) on the catalyst surface, especially in reactions like catalytic cracking of hydrocarbons. This can cover the active sites and block the reactants from accessing them. In petroleum refining, coke can build up on catalysts used for cracking large hydrocarbons into smaller ones, leading to reduced performance.

3.1.5 Leaching: It happens when the catalyst material itself dissolves or is removed from the surface due to the reaction conditions, such as high temperature, pressure, or exposure to certain chemicals. This leads to a loss of the catalyst's active components. In heterogeneous catalysis involving metal catalysts, leaching of precious metals like platinum can occur, reducing the catalyst's efficiency (G. L. Chiarello et al ., 2014)

3.1.6 Thermal Deactivation: It is caused by exposure to high temperatures, which can lead to changes in the physical properties of the catalyst, such as sintering or phase changes in solid catalysts. High temperatures can cause certain metals, such as copper, to undergo phase transitions that reduce their catalytic ability.

3.2 Methods of Deactivation Recovery:

3.2.1 Regeneration: It is the process of restoring the activity of a deactivated catalyst. This can involve cleaning the catalyst surface to remove poisons, coke, or other contaminants. In catalytic reforming, a coke-covered catalyst can often be regenerated by burning off the coke in an oxygen-rich atmosphere at high temperatures.

3.2.2 Reactivation: It can refer to the restoration of a catalyst by restoring its original properties, such as re-precipitating metal particles or rebalancing the surface structure. If a catalyst is poisoned by sulfur, it can sometimes be treated with a hydrogen treatment to remove the sulfur and restore activity.

3.2.3 Replacement: If the catalyst is severely deactivated or its material is irreversibly altered, the best option may be to replace it with a fresh catalyst. In cases of severe sintering or leaching, replacing the catalyst may be the only viable solution.

4. Recent Trends in Catalysis:

Recent trends in catalysis reflect the rapid advancements in both the fundamental understanding of catalytic processes and the development of new materials and technologies. The goal of these trends is often to improve reaction efficiency, minimize environmental impact, and make industrial processes more sustainable. Here are some of the key trends in catalysis:

4.1 Nanocatalysis: Nanocatalysts are catalysts that operate at the nanoscale (typically with particle sizes under 100 nm). They offer increased surface area, enhanced reactivity, and the ability to tailor properties like size, shape, and electronic structure to optimize catalytic performance (Viacheslav Iablokov *et al.*, 2012). Nanocatalysts are used in processes like hydrogenation, fuel cells, and environmental protection (e.g., air purification or CO_2 conversion). Research is focusing on the design of nanostructured catalysts with enhanced stability and activity, often using metal nanoparticles (e.g., gold, platinum) or metal oxides (e.g., titanium dioxide) (Le *et al.*, 2020) .

4.2 Biocatalysis and Green Chemistry: Biocatalysts (enzymes) are gaining increasing attention due to their specificity, efficiency, and mild operating conditions. They are widely used in the pharmaceutical, food, and biofuels industries. Green Chemistry emphasizes the use of environmentally friendly and sustainable catalysts that reduce the use of toxic solvents and harsh reagents. There is an ongoing effort to enhance the stability and activity of biocatalysts and to develop biomimetic catalysts, which mimic the behavior of enzymes for synthetic chemical reactions (American Chemical Society, 2014).

4.3 Electrocatalysis: It involves catalysts that facilitate reactions at the electrode surface in electrochemical processes. These are particularly important in fuel cells, water splitting (hydrogen production), and CO_2 reduction. Research is focused on improving the efficiency of electrocatalysts, especially for renewable energy applications like hydrogen production (from water) and CO_2 conversion to useful chemicals (e.g., methanol or carbon monoxide). Developing noble-metal-free catalysts (e.g., based on iron, copper, or nickel) for water splitting or CO_2 reduction to lower the cost and make these technologies more scalable. (Huan Cong and John A. Porco, Jr. 2011).

4.4 Catalyst Design via Computational Chemistry: Advances in computational chemistry and machine learning are allowing for the design of new catalysts and optimization of existing ones by predicting reaction pathways, identifying new materials, and understanding the mechanistic details of catalytic processes (Mitsudome *et al.*, 2008). High-throughput screening combined with computational models is accelerating the discovery of new catalysts, particularly in areas like organic synthesis and energy production. Using computational tools like density functional theory (DFT) to predict catalyst properties or develop new heterogeneous catalysts for reactions like CO_2 hydrogenation or oxidation.

4.5 Sustainable Catalysis and Circular Economy: Sustainable catalysis is focused on developing catalysts that promote reactions with minimal waste, lower energy consumption, and reduce the use of hazardous materials. Catalysis is increasingly being used to facilitate the conversion of waste materials into valuable products. This is part of the broader circular economy movement, which aims to reduce waste and maximize the reuse of materials. Catalysts that convert CO_2 into fuels or chemicals are being developed as a way to combat climate change and make use of greenhouse gases (Allyson J. Boyington *et al.*, 2019).

4.6 Photocatalysis and Solar-Driven Reactions: Photocatalysis uses light (typically sunlight) to drive catalytic reactions, especially in processes like water splitting (for hydrogen production) and air purification. Photocatalysts are being developed for solar energy harvesting and CO_2 reduction, aiming to mimic photosynthesis in plants for sustainable fuel production. Titanium dioxide (TiO_2) and other semiconductors are being explored as photocatalysts for solar fuel generation, where they use sunlight to drive the splitting of water or the reduction of CO_2 (Gupta *et al.*, 2021).

4.7 Hybrid Catalysis (Heterogeneous + Homogeneous): Hybrid catalysis combines the advantages of both heterogeneous and homogeneous catalysts. This approach allows for better selectivity, reactivity, and the ability to recover and reuse the catalyst. Researchers are exploring dual-phase or dual-function catalysts, which integrate both types of catalysis in a single system for improved reaction efficiency.

5. Opportunities in Fields of Catalysis:

The field of catalysis is full of opportunities, especially in the context of advancing sustainability, energy efficiency, and chemical innovation. As global challenges such as climate change, resource depletion, and pollution intensify, catalysts can play a crucial role in shaping solutions for these issues. Here are some key opportunities in catalysis:

5.1 Sustainable Energy Production and Storage:

Hydrogen Economy: Catalysts are key to making hydrogen production via water splitting (electrolysis) more efficient and cost-effective. Hydrogen is seen as a clean energy carrier that can replace fossil fuels, especially for sectors like transportation and industrial heating.

Fuel Cells: Research in electrocatalysts for hydrogen fuel cells (e.g., proton exchange membrane fuel cells) offers opportunities for more efficient energy storage and conversion. Catalysts like platinum (Pt) and novel alternatives can enhance the efficiency and reduce the cost of fuel cells for both portable and stationary applications. (Peter Priecel *et al.,* 2019).

5.2 Green Chemistry and Waste Valorization:

Waste-to-Value: Converting industrial waste (such as plastic or organic waste) into valuable chemicals or fuels using catalysis offers significant environmental and economic opportunities. Catalysts can help break down waste polymers into usable monomers or fuels, supporting a circular economy (American Chemical Society 2014).

Biomass Conversion: Catalysts are essential for converting renewable biomass (agricultural waste, wood, algae) into biofuels, chemicals, and materials. The development of effective catalysts for biomass liquefaction, bioethanol production, or biodiesel synthesis can help transition industries toward renewable feedstocks (K. Aasberg-Petersen *et al.*, 2011).

5.3 Environmental Protection and Pollution Control:

Emission Control: Catalysts are already integral to automotive catalytic converters, which reduce harmful emissions from vehicle exhausts. However, there's an ongoing need for more efficient and durable catalysts to handle higher emission standards and toxic gases like NO_x, CO, and particulate matter (Carl A. Denard *et al.,* 2013).

Air Purification: The development of catalysts for indoor and outdoor air purification (e.g., removing VOCs, nitrogen oxides, and ozone) presents opportunities for improving air quality in urban areas.

Water Treatment: Catalysts can also be used in advanced water treatment technologies . For example, photocatalysts are being developed for desalination and the removal of harmful chemicals or pathogens from water sources, enabling better access to clean water.

5.4 Energy-Efficient Chemical Manufacturing:

Catalysis in Petrochemicals: Opportunities exist in refining processes like hydrocracking, alkylation, and isomerization where catalysts can improve selectivity and yield, leading to lower energy consumption and higher efficiency in producing valuable fuels and chemicals (Yu Wang *et al.,* 2014).

Renewable Chemical Synthesis: The transition from petroleum-based chemicals to bio-based chemicals relies heavily on biocatalysts and homogeneous/heterogeneous catalysts that can convert renewable resources like sugars or plant oils into valuable industrial chemicals and pharmaceuticals (G. L. Chiarello *et al.,* 2014)

5.5 Catalysis for Fine Chemicals and Pharmaceuticals:

Asymmetric Catalysis: There is growing demand for highly selective catalysts in the synthesis of chiral molecules (used in drugs, agrochemicals, and fine chemicals). Opportunities lie in developing more efficient catalysts for asymmetric synthesis, which allows for the precise control of molecular chirality without unwanted by-products (Rajesh Koirala *et al.,* 2016).

Pharmaceutical Manufacturing: Catalysts can improve the efficiency of drug manufacturing by enabling green synthetic pathways and reducing the need for hazardous reagents or high energy costs (Ojeda *et al.,* 2009). Catalysts also offer opportunities for making customized medications through targeted drug delivery systems or personalized medicine (Ivan V. Kozhevnikov 2006).

Metathesis Reactions: The development of catalysts for olefin metathesis is revolutionizing the production of polymers and specialty chemicals, creating new opportunities for innovation in both materials and pharmaceuticals (Peter Priecel *et al.,* 2019).

Conclusion:

The field of catalysis is poised for significant advancements that will contribute to the transition toward a more sustainable, efficient, and environmentally-friendly future. From energy production to pollution control, fine chemicals, and carbon management, catalysts are at the heart of many transformative technologies. As challenges related to climate change, resource depletion, and environmental degradation grow, opportunities in catalysis will continue to expand, making it an exciting area for innovation, investment, and research.

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HYDROGEN PRODUCTION AND STORAGE: MODERN METHODS AND MATERIAL INNOVATIONS

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Abstract:

This paper reviews current and emerging hydrogen production and storage technologies, emphasizing their importance in sustainable energy systems. It highlights methods like steam methane reforming, electrolysis (renewable and nuclear-powered), thermochemical, and biological processes, noting their efficiency and environmental impact. Hydrogen's high calorific value and clean-burning nature make it suitable for transport, power, and industry. Advances in materials and infrastructure are key to enabling a low-carbon hydrogen economy and supporting the global energy transition.

Keywords: Renewable Energy, Electrolysis, Nuclear Energy, Thermochemical Water Splitting, Biomass Gasification, Hydrogen Storage.

Introduction:

Hydrogen is increasingly recognized as a promising clean fuel that has the potential to play a central role in the global transition toward sustainable energy systems. When consumed in a fuel cell, hydrogen reacts electrochemically with oxygen to generate electricity, water vapor, and heat, without releasing carbon dioxide (CO_2) or other pollutants. This zero-emission profile makes hydrogen an attractive energy carrier for a wide range of applications, particularly in sectors that are hard to decarbonize, such as transportation, power generation, and heavy industry.

A key property that contributes to hydrogen's appeal is its exceptionally high calorific value. The calorific value refers to the amount of energy released during the complete combustion of one gram of fuel in oxygen. Hydrogen has the highest known calorific value among fuels—approximately 150 kJ g^{-1}, which means it can release significant energy relative to its mass. This high energy density, combined with its clean combustion, positions hydrogen as a superior alternative to fossil fuels in applications ranging from fuel cell vehicles to distributed electricity generation.

Hydrogen is also highly versatile in terms of production. Hydrogen can be produced through a variety of methods, utilizing both conventional and renewable energy sources. One of the most widely used methods today is steam methane reforming (SMR), a thermal process that extracts hydrogen from natural gas. Although efficient and cost-effective, this method emits carbon dioxide as a by-product unless coupled with carbon capture technologies. A cleaner alternative is electrolysis of water, where electricity is used to split water molecules into hydrogen and oxygen. When powered by renewable energy sources such as solar or wind, this process yields green hydrogen, which is completely free of carbon emissions. Nuclear energy can also contribute to hydrogen production by providing the high temperatures and electricity necessary for high-temperature water splitting processes. Additionally, biomass and biological processes offer sustainable pathways for hydrogen generation, using microorganisms such as algae or bacteria to produce hydrogen through fermentation or biophotolysis. These diverse production methods allow hydrogen to be integrated into various energy systems, contributing to a cleaner, low-carbon future.

Hydrogen can be stored for future use, transported through pipelines or in liquid/compressed form, and used on-demand to produce electricity or heat. This flexibility makes hydrogen a crucial enabler of energy security, grid stability, and decarbonization across energy systems.

The development of hydrogen fuel technologies is a major focus of scientific and engineering research today. Countries around the world are investing heavily in hydrogen infrastructure, fuel cell innovation, and green hydrogen production methods to meet climate goals and reduce dependence on fossil fuels. As technological advances continue to improve the efficiency, safety, and economics of hydrogen production and storage, its role in a low-carbon future is expected to grow significantly. Table 1 shows different sources of hydrogen production.

Table 1: Different sources of hydrogen

Color	Production Source
Green	Hydrogen produced from low-emission sources such as biomass
Turquoise	Thermal splitting of methane
Blue	Hydrocarbons with carbon capture and storage
Gray	Fossil hydrocarbons, mainly steam reforming of natural gas
Brown or black	Fossil hydrocarbons:
Red, Pink or Purple	Nuclear Power
Yellow	Solar Photovoltaics
Gold or White	Hydrogen that occurs naturally deep within the Earth's crust

Production of hydrogen

1. Electrolytic method

Water can be separated into oxygen and hydrogen through a process called electrolysis. Electrolytic processes take place in an electrolyzer, which functions much like a fuel cell in reverse- instead of using the energy of a hydrogen molecule, like a fuel cell does, an electrolyzer creates hydrogen from water molecules.

Electrolysis is a promising option for carbon-free hydrogen production from renewable and nuclear resources. Electrolysis is the process of using electricity to split water into hydrogen and oxygen. This reaction takes place in a unit called an electrolyzer. Electrolyzers can range in size from small, appliance-size equipment that is well-suited for small-scale distributed hydrogen production to large-scale, central production facilities that could be tied directly to renewable or other non-greenhouse-gas-emitting forms of electricity production. The anode (positive electrode) is typically made of nickel and copper and is coated with oxides of metals such as manganese, tungsten and ruthenium.

Polymer Electrolyte Membrane Electrolysers

Construction: Like fuel cells, electrolysers consist of an anode and a cathode separated by an electrolyte. Different electrolysers function in different ways, mainly due to the different type of electrolyte material involved and the ionic species it conducts.

Working

In a polymer electrolyte membrane (PEM) electrolyzer Figure 1, Water reacts at the anode to form oxygen and positively charged hydrogen ions (protons). The electrons flow through an external circuit and the hydrogen ions selectively moves across the PEM to the cathode.

The catalyst allows quick pairing of atomic hydrogen into pairs at the electrode surface and thereby increases the rate of hydrogen production. Without the catalyst, atomic hydrogen would build up on the electrode and block current flow. A gas separator, or diaphragm, is used to prevent intermixing of hydrogen and oxygen although it allows free passage of ions.

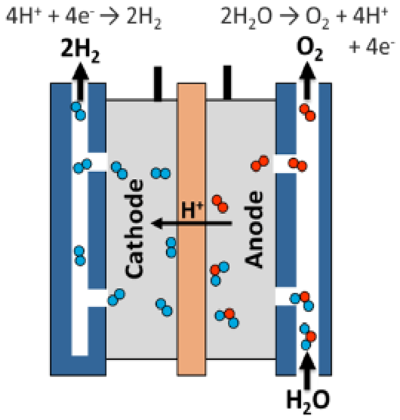

Fig. 1: Polymer Electrolyte Membrane Electrolysers

- Water reacts at the anode to form oxygen and positively charged hydrogen ions (protons).
- The electrons flow through an external circuit and the hydrogen ions selectively move across the PEM to the cathode.

- At the cathode, hydrogen ions combine with electrons from the external circuit to form hydrogen gas.

$$\text{Anode Reaction: } 2H_2O \rightarrow O_2 + 4H^+ + 4e^-$$

$$\text{Cathode Reaction: } 4H^+ + 4e^- \rightarrow 2H_2$$

2. Thermal decomposition of water

Thermal decomposition of water (also known as **thermolysis of water**) is a process where water (H_2O) is decomposed into hydrogen (H_2) and oxygen (O_2) using high temperatures. This method is a direct way to produce hydrogen, but it requires extremely high temperatures, generally exceeding 2,500°C (4,532°F) to drive a series of chemical reactions that produce hydrogen. The chemicals used in the process are reused within each cycle, creating a closed loop that consumes only water and produces hydrogen and oxygen.

- Concentrating sunlight onto a reactor tower using a field of mirror "heliostats," A **heliostat** is a device that includes a mirror, usually a plane mirror, which turns to keep reflecting sunlight toward a predetermined targetas shown below

Thermochemical water splitting cycles, the "direct" two-step cerium oxide thermal cycle. It requires higher operating temperatures compared with the more complicated hybrid cycles.

$$\textbf{Reduction:}\quad 2Ce^{(IV)}O_2 \longrightarrow Ce^{(III)}{}_2O_3 + {}^1/_2O_2$$

$$\textbf{Oxidation:}\quad Ce^{(III)}{}_2O_3 + H_2O \longrightarrow 2Ce^{(IV)}O_2 + H_2$$

$$\textbf{Net reaction:}\quad H_2O \longrightarrow {}^1/_2O_2 + H_2$$

3. Chemical extraction

Hydrogen production through chemical extraction refers to processes that generate hydrogen gas (H_2) by chemically breaking down hydrogen-containing compounds. The most common chemical methods for hydrogen extraction includes Steam Methane Reforming (SMR), Coal Gasification, Biomass Gasification.

a) Steam Methane Reforming (SMR)

Process:

SMR is the most widely used method for hydrogen production. It involves reacting methane (CH_4) with steam (H_2O) at high temperatures (700–1,000°C) in the presence of a catalyst. In steam-methane reforming, methane reacts with steam under 3–25 bar pressure (1 bar = 14.5 psi) in the presence of a catalyst (Nickel Based) to produce hydrogen, carbon monoxide, and a relatively small amount of carbon dioxide. Steam reforming is endothermic-that is, heat must be supplied to the process for the reaction to proceed.

Subsequently, in what is called the "water-gas shift reaction," the carbon monoxide and steam are reacted using a catalyst to produce carbon dioxide and more hydrogen. In a final process step called "pressure-swing adsorption," carbon dioxide and other impurities are removed from the gas stream, leaving essentially pure hydrogen. Steam reforming can also be used to produce hydrogen from other fuels, such as ethanol, propane, or even gasoline.

Chemical Reactions:

Steam-methane reforming reaction

$$CH_4 + H_2O\ (+heat) \longrightarrow CO + 3H_2$$

Water-gas shif reaction

$$CO + H_2O \longrightarrow CO_2 + H_2\ (+small\ amount\ of\ heat)$$

This produces hydrogen along with carbon dioxide (CO_2) as a byproduct. High CO_2 emissions make this method less environmentally friendly, unless combined with carbon capture and storage (CCS) technologies.

b) Coal Gasification

In this method, coal is converted into syngas (a mixture of hydrogen, carbon monoxide, and other gases) by reacting coal with oxygen and steam under high temperatures.

Chemical Reaction:

$$C + H_2O \longrightarrow CO + H_2$$

Hydrogen is extracted, but the process also produces significant CO_2. Like SMR, coal gasification emits CO_2 and is generally not considered sustainable without CCS.

c) Biomass Gasification

Biomass (plant or organic material) is heated to produce syngas, which contains hydrogen, carbon monoxide, and other compounds. The hydrogen is then separated.

Chemical Reaction:

$$Biomass + O_2 + H_2O \longrightarrow CO + H_2 + CO_2$$

Hydrogen can be extracted, with fewer carbon emissions compared to fossil fuel-based methods. It's a more sustainable approach when using renewable biomass. As hydrogen becomes a key part of clean energy systems, methods that minimize CO_2 emissions, such as electrolysis using renewable energy, are likely to grow in importance.

4. Nuclear Energy

Hydrogen production using nuclear energy is a promising path for large-scale, carbon-free hydrogen production. Methods such as

- ✓ electrolysis using nuclear electricity,
- ✓ High-Temperature Steam Electrolysis (HTSE)
- ✓ Thermochemical Water-Splitting Using Nuclear Heat

could significantly contribute to clean hydrogen production in the future. While technology is not yet commercially widespread, ongoing research and development in nuclear reactor designs and hydrogen production methods hold great potential for contributing to the hydrogen economy.

High-Temperature Steam Electrolysis (HTSE)

Process: HTSE, also known as **solid oxide electrolysis**, is a more efficient form of electrolysis that uses both heat and electricity to split water. The process requires high temperatures, typically between 700°C and 900°C, which can be provided by nuclear reactors.

Efficiency: The high temperatures reduce the amount of electricity needed to perform the electrolysis, making it more efficient than conventional low-temperature electrolysis.

Nuclear Role: Advanced nuclear reactors, such as Generation IV reactors or high-temperature gas-cooled reactors (HTGRs), can provide the necessary heat and electricity for HTSE.

Advantages:

- Higher efficiency than traditional electrolysis due to the use of heat.
- Potential for large-scale hydrogen production without carbon emissions.

Drawbacks: The technology is still in development, and the infrastructure and materials needed to handle such high temperatures pose challenges.

5. Direct solar water splitting process

Direct solar water splitting, also known as photoelectrochemical (PEC) water splitting, is a method of producing hydrogen using sunlight to directly split water (H_2O) into hydrogen (H_2) and oxygen (O_2). This process mimics photosynthesis in plants, using sunlight to drive the reaction and produce clean hydrogen fuel. It is considered a promising approach for green hydrogen production because it does not require any fossil fuels and emits no greenhouse gases.

Photoelectrochemical (PEC) Cell:

- A PEC cell is the core of the direct solar water splitting process. It consists of two electrodes: a **photoanode** and a **photocathode**, submerged in water.
- The photoanode absorbs sunlight and generates charge carriers (electrons and holes), which are then used to split water molecules.
- The process involves:

Water Oxidation at the **photoanode** (producing oxygen).

At the photoanode:

$$2H_2O \longrightarrow O_2 + 4H^+ + 4e^-$$

Water Reduction at the **photocathode** (producing hydrogen).

At the photocathode:

$$4H^+ + 4e^- \longrightarrow 2H_2$$

The overall water-splitting reaction is

$$2H_2O + \text{sunlight} \longrightarrow 2H_2 + O_2$$

Working

Absorption of Sunlight:

- The **photoanode** is typically made of a semiconductor material (e.g., titanium dioxide (TiO_2), iron oxide (Fe_2O_3), or newer materials like bismuth vanadate ($BiVO_4$)) that can absorb photons (light particles) from sunlight. When these photons are absorbed, they excite electrons, creating electron-hole pairs.
- **Water Splitting Reaction**:

  The excited electrons move toward the **photocathode**, where they reduce protons (H^+) to produce hydrogen gas (H_2).

  Meanwhile, the holes in the **photoanode** move toward the surface, where they oxidize water (H_2O), releasing oxygen gas (O_2).

  Separation of Hydrogen and Oxygen:
- The hydrogen and oxygen gases are produced at different electrodes and are separated within the system. The hydrogen is collected for use as fuel, while the oxygen is released as a byproduct.

Advantages of Direct Solar Water Splitting:

1. Clean and Renewable:

Solar water splitting is a completely clean process as it only uses sunlight and water to produce hydrogen, without emitting carbon dioxide (CO_2) or other pollutants.

2. Direct Conversion:

Unlike other hydrogen production methods that rely on intermediate processes (such as generating electricity for electrolysis), PEC cells directly convert solar energy into hydrogen, which could potentially reduce the complexity and cost of the system.

3. Potential for High Efficiency:

Theoretically, the process can achieve high conversion efficiency if optimal semiconductor materials and cell designs are developed.

4. Modular and Scalable:

PEC systems can be designed as modular units that are scalable for small or large-scale hydrogen production depending on the available sunlight and water resources.

6. Hydrogen from the decomposition of materials containing hydride anions.

Hydrogen production from the decomposition of materials containing hydride anions (H^-) involves the breakdown of compounds in which hydrogen exists as an anion, rather than as a molecule (H_2). Hydride anions are typically present in ionic or covalent hydrides, where hydrogen is bound to metals or other elements with a negative charge. The release of hydrogen from these materials occurs through thermal decomposition, chemical reactions, or catalysis.

Hydride Anion (H^-): This is a hydrogen atom that has gained an extra electron, giving it a negative charge. Hydride anions are highly reactive and act as reducing agents.

Materials Containing Hydride Anions: These materials can be metal hydrides, chemical hydrides, or complex hydrides. In these compounds, hydrogen is stored in the form of H^- anions and can be released through appropriate decomposition methods.

In metal hydrides, hydrogen exists in the form of H^- bound to metal cations (e.g., Mg^{2+} in MgH_2). When these hydrides are heated, they decompose to release hydrogen gas (H_2).

Ex: Magnesium hydride (MgH_2):

$$MgH_2 \xrightarrow{\text{Heat}} Mg + H_2$$

- **Process**: When heated, the metal hydride breaks down, releasing hydrogen gas and leaving behind the metal in its elemental form (e.g., Mg).
- **Applications**: Thermal decomposition of metal hydrides is commonly used in hydrogen storage systems, where the hydride is heated to release hydrogen for use in fuel cells.

Many materials containing hydride anions will release hydrogen when they react with water. In these reactions, hydride anions (H^-) react with water to form hydrogen gas (H_2) and hydroxide ions (OH^-).

Ex 1: Sodium hydride (NaH):

$$NaH + H_2O \longrightarrow NaOH + H_2$$

Ex 2: Lithium hydride (LiH)

$$LiH + H_2O \longrightarrow LiOH + H_2$$

- **Process**: Hydride anions react with water to produce hydrogen gas. This method can be used for on-demand hydrogen generation, especially in portable applications.
- **Advantages**: This is a relatively simple process that can occur at room temperature and doesn't require high energy input.

Hydrogen storage in solids

Hydrogen storage in solids refers to methods in which hydrogen is stored within solid materials, rather than as a compressed gas or cryogenic liquid. Solid-state hydrogen storage offers several advantages, including higher volumetric hydrogen density, improved safety, and the potential for more efficient and compact systems.

Solid hydrogen storage materials include metal hydrides, chemical hydrides, complex hydrides, adsorbent materials, and nanomaterials. These materials can absorb hydrogen and release it under certain conditions, making them useful for a variety of applications, from fuel cells to portable power systems.

Metal Hydrides: Metal hydrides are one of the most studied materials for solid-state hydrogen storage. They store hydrogen by chemically binding it to metals, forming a hydride phase. Hydrogen can be released by changing temperature or pressure.

- Ex: Magnesium hydride (MgH_2), sodium hydride (NaH), titanium hydride (TiH_2), and palladium hydride (PdHx).

Storage Capacity: Metal hydrides can store hydrogen in high densities (up to 7-8% by weight for some materials like MgH_2).

Mechanism: The general reaction involves the absorption of hydrogen gas by the metal to form a metal hydride. The process is reversible, meaning hydrogen can be re-released by applying heat or lowering pressure.

$$\text{Metal} + H_2 \rightleftharpoons \text{Metal Hydride}$$

Advantages: High volumetric hydrogen density, safety (since hydrogen is stored in solid form), and reversibility (metal hydrides can absorb and desorb hydrogen repeatedly).

Disadvantages: Some metal hydrides require high temperatures (300°C to 400°C) for hydrogen release, and the materials can be heavy, limiting their use in weight-sensitive applications like transportation.

Ammonia in the storage of hydrogen

Ammonia (NH_3) is emerging as a promising carrier for hydrogen storage and transportation due to its high hydrogen content, ease of liquefaction, and well-established infrastructure for production, storage, and transport. Ammonia is composed of 17.6% hydrogen by weight, and it can be synthesized from nitrogen and hydrogen using the Haber-Bosch process, which is widely utilized in the chemical industry.

When needed, hydrogen can be extracted from ammonia through various processes, such as thermal decomposition or catalytic cracking. The ability to store and transport ammonia under relatively mild conditions makes it an attractive hydrogen carrier for long-distance transportation, energy storage, and fuel cells.

Advantages of using Ammonia

High Hydrogen Content: Ammonia contains 17.6% hydrogen by weight, making it one of the most hydrogen-rich molecules available. This means that for a given mass, ammonia can store a significant amount of hydrogen.

Ease of Liquefaction: Ammonia liquefies at -33°C at atmospheric pressure, which is much more achievable than the cryogenic conditions required to liquefy hydrogen itself (-253°C). Liquefied ammonia is easier to store and transport than gaseous or liquid hydrogen.

Cost-Effective: The cost of producing and handling ammonia is relatively low compared to other hydrogen storage methods, and its distribution network is already in place.

Lower Explosiveness: Although ammonia is toxic, it is less flammable and explosive compared to hydrogen, making it potentially safer for large-scale storage and transportation.

Methods for Storing and Extracting Hydrogen from Ammonia:

1. Ammonia Synthesis and Storage:

Production: Ammonia is typically produced by reacting hydrogen with nitrogen in the Haber-Bosch process:

$$N_2 + 3H_2 \xrightarrow{\text{Catalyst}} 2NH_3$$

Storage: Once produced, ammonia can be stored in liquid form under mild pressures (10-15 bar) at ambient temperatures or refrigerated to maintain its liquid state at -33°C at atmospheric pressure.

2. Ammonia Decomposition (Cracking): Hydrogen can be extracted from ammonia by decomposing it into hydrogen and nitrogen gases. This process, known as ammonia cracking, typically requires a catalyst and high temperatures (450-600°C). The decomposition reaction is as follows:

$$2NH_3 \xrightarrow{\text{Heat, Catalyst}} N_2 + 3H_2$$

Catalysts: Common catalysts for ammonia cracking include metals such as nickel (Ni), iron (Fe), and ruthenium (Ru). These catalysts help lower the activation energy required for breaking the nitrogen-hydrogen bonds in ammonia.

Applications: The hydrogen produced through ammonia cracking can be used in fuel cells to generate electricity or in other hydrogen-based energy systems.

Hydrogen storage in reversible organic liquids

This also known as Liquid Organic Hydrogen Carriers (LOHCs), is an innovative and promising method for storing and transporting hydrogen. In this system, organic compounds are chemically hydrogenated (hydrogen is added) and later dehydrogenated (hydrogen is released), enabling the reversible storage of hydrogen in a liquid medium. This approach offers the safety and convenience of liquid storage at ambient conditions, eliminating the need for high-pressure tanks or cryogenic temperatures.

Some commonly studied LOHCs include: Ex 1: Toluene/ Methylcyclohexane (MCH):

- Hydrogenated form: Methylcyclohexane (C_6H_{11}-CH_3)
- Dehydrogenated form: Toluene (C_6H_5-CH_3)

$$C_6H_5\text{-}CH_3 \text{ (Toluene)} + 3H_2 \rightleftharpoons C_6H_{11}.CH_3 \text{ (MCH)}$$

Ex 2: N-ethylcarbazole:

Hydrogenated form: Perhydro-N-ethylcarbazole

Dehydrogenated form: N-ethylcarbazole

$$\text{N-ethylcarbazole} + 9H_2 \rightleftharpoons \text{Perhydro-N-ethylcarbazole}$$

This compound can store multiple hydrogen molecules, making it an efficient carrier for hydrogen storage.

Working:

Hydrogenation: The liquid organic compound (e.g., toluene) is exposed to hydrogen at elevated temperatures and pressures in the presence of a catalyst. The compound chemically bonds with hydrogen, forming a hydrogen-rich version of the molecule (e.g., methylcyclohexane in the case of toluene).

- This process occurs in a **hydrogenation plant** where hydrogen from an external source (e.g., from electrolysis or steam methane reforming) is chemically added to the LOHC.

Storage and Transport: Once hydrogenated, the LOHC can be stored in standard liquid containers or transported in **tanker trucks**, **ships**, or **pipelines** without the need for pressurization or refrigeration. This makes LOHCs a convenient and safe method for hydrogen storage and long-distance transport.

Dehydrogenation: When the stored hydrogen is needed, the hydrogen-rich LOHC is heated (usually at 150°C to 300°C) or passed over a catalyst in a **dehydrogenation plant**, causing it to release the hydrogen and revert to its original form.

- The hydrogen gas can then be fed into fuel cells, combustion engines, or other applications requiring hydrogen energy.
- The dehydrogenated LOHC can be collected and sent back to the hydrogenation plant to restart the cycle, making the process fully reversible.

Conclusion:

The comprehensive review underscores hydrogen's significant potential as a clean and versatile energy carrier, emphasizing advancements in production and storage technologies. The development of sustainable methods—such as electrolysis powered by renewable energy, nuclear-driven processes, and biomass gasification—highlight the pathway toward a low-carbon hydrogen economy. Continued innovation and infrastructure investment are critical for harnessing hydrogen's high energy density and integrating it into various sectors, thereby enabling a transition to sustainable and decarbonized energy systems for the future.

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SUSTAINABLE DEVELOPMENT THROUGH SCIENCE AND TECHNOLOGY

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Abstract:

Science and technology play an important role in the pursuit of sustainable development, especially in the following categories: Energy use: The key technologies of sustainable development include new energy and propulsion technologies that will help reduce emissions of climate-damaging greenhouse gases. The mission is designed with the objectives to bring sustainability in the livelihood system through Science and Technology interventions, and to strengthen the technology delivery mechanism for livelihood and quality of life. Science and technology for a sustainable future help us understand our environment and our impact on it, which is essential for making smart decisions about how to use our resources. It can also help us find solutions to problems, such as climate change and pollution, and improve the quality of life for all people.

Introduction:

Few threads in the vast tapestry of human existence have become ingrained in daily life as deeply as science and technology. They have an ever-present influence on everything, from the easiest chores to the most difficult undertakings, influencing how we work, live, and engage with the world. Unquestionably, science and technology have a significant and indisputable impact on daily life, influencing every facet of our existence with a rainbow of discoveries and breakthroughs. For a moment, imagine the routine of waking up to the soft sound of a smartphone alarm and then instantly viewing weather reports sent from satellites in orbit high overhead. With the help of GPS navigation systems, we maneuver through busy city streets during the course of the day, effortlessly interacting via a global network of interconnected devices with coworkers and loved ones on different continents. Thanks to technological advancements, even routine tasks like grocery shopping can be made more enjoyable.

Online delivery services and automated checkout systems make this possible. In today's highly interconnected world, human beings, as part of the biosphere, are considered the major force impacting our planet; therefore, the human species is facing a crucial transition period. In this uncertain stage of human history, vulnerabilities and risks are high but also are opportunities for socio– ecological changes and transformations. What is important is that global sustainability becomes the foundation of our interconnected and interdependent global economic, social and environmental systems.The reality however is that we still promote a model of development based on the premises that development is a process of structural changes that will imply a series of historic steps that developing countries have to follow in order to move from a traditional society to a more modern one in order to reach the present levels of mass consumption of developed countries**.** Technology provides sustainable solutions through renewable energy sources such as solar, wind, and hydroelectric power. These sources of energy are clean, affordable, and renewable, and their integration can reduce greenhouse gas emissions, mitigate climate change, and promote development. Overall, technology empowers environmental conservation efforts by providing innovative tools and solutions to safeguard ecosystems, preserve biodiversity, and promote sustainable development for present and future generations. Technology help with sustainability like, agriculture, sustainable technology is used to monitor the water level and health of crops, in order to increase yield and optimize water usage. Drones can also be used to monitor crop health with cameras and machine learning-based vision AI. Drones can even apply fertilizer. Technology in achieving the sustainable development goals, in various sector like, technology holds immense potential to drive sustainable development and accelerate climate action. It serves as a catalyst for transformative changes across industries and societies by harnessing innovations in renewable energy, smart agriculture, water management, waste reduction and informing consumer behaviours. Technology has always played a vital role in economic development, but its impact has become increasingly significant in recent decades. Technological advancements have led to new industries and products, increased productivity, and improved efficiency in existing industries.

Science important to sustainability future help us understand our environment and our impact on it, which is essential for making smart decisions about how to use our resources. It can also help us find solutions to problems, such as climate change and pollution, and improve the quality of life for all people**.** Technology used to manage resources more sustainably for example, smart energy systems in homes and businesses help reduce electricity consumption by adjusting outputs based on real-time usage data.

Role of Science and Technology:

To develop innovative, green solutions to address the climate, food and energy crisis facing the world today, science, technology, research and development capacities for sustainable development must be strengthened. Open Access to scientific information is a prerequisite for generating knowledge for sustainable development. Science supports the prudent management for the daily survival and future development of humanity. For this, it will be essential to enhance scientific understanding, improve long term scientific assessments, strengthen scientific capacities in all countries and ensure that the sciences are responsive to emerging needs. At first step towards improving the scientific basis for these strategies is a better understanding of land, oceans, atmosphere and their interlocking water, nutrient and biogeo-chemical cycles and energy flows which all form part of the earth system.The sciences can provide this understanding through increased research into the underlying ecological processes and through the application of modern, effective and efficient tools that are now available such as remote sensing devices, robotic monitoring instruments and computing and modelling capabilities.Science and Technology play in the development progress of the country like, Science and technology have made it easier for people to communicate with other people across the world. They also helped in decreasing the costs of production leading to business growth as well as contributing to the development in the agriculture sector, education sector, and industrial/manufacturing sector. And also, important sustainable technology offers an opportunity to reframe our relationship with existing innovations in a way that helps address environmental and societal challenges.

For instance, companies can leverage technology solutions like the Internet of Things to optimize routes and make fleet management more sustainable. The goal of these technologies is to drastically reduce environmental and ecological risks and to create a sustainable product. Sustainability in technology can be defined in a few ways: Substitution. The technology fosters a shift from non-biodegradable to biodegradable materials in its production. Let's go into five ways technology can save you time, reduce costs, and get rid of your event headaches. Like, Menu management features save time, reduce food cost and waste with technology, Tech saves time with efficient communication, Staff events efficiently with technology etc. And technology in increasing productivity to Perhaps the biggest way that technology can improve productivity is through time-saving tools. This is especially evident with automation. By taking mundane or repetitive tasks out of the hands of employees, you can free them up to do more creative work. Science contributes to technology in at least six ways:

1. new knowledge which serves as a direct source of ideas for new technological possibilities;
2. source of tools and techniques for more efficient engineering design and a knowledge base for evaluation of feasibility of designs;
3. research instrumentation.

The impact of science and technology on sustainable future

Understanding the impact of technological advancements on everyday life is paramount for several reasons like,

- First and foremost, it enables us to fully utilize technology to tackle urgent global issues like socioeconomic inequality, climate change, and healthcare disparities. We can create novel solutions that enhance the standard of living for people and communities globally by utilizing scientific knowledge and technological resources.
- Second, by understanding the effects of technology, we can better understand and anticipate how to deal with the complexity of today's world. We need to develop a critical

mentality that weighs the advantages and disadvantages of new technologies as we deal with the lightning-fast speed of technological change.

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- This requires posing challenging queries regarding the long-term effects of the technological decisions we make and promoting laws that put the welfare of the public above personal benefit.
- Furthermore, cultivating digital literacy and enabling people to make knowledgeable decisions about their interactions with technology depend on an understanding of how technological advancements affect day-to-day living. Being technologically literate is now essential for participating fully in social, political, and economic life in a society that is becoming more and more digitalized. We can reduce the likelihood of technology-related harms and advance digital inclusion for all by giving people the information and abilities they need to responsibly traverse the digital world.
- Positive impact of technology on society, technology's development and use have helped societies in increasing productivity, expanding service accessibility, and improving overall well-being.
- Healthcare & wellness advancements technology has the potential to significantly improve health and healthcare systems as we know them. From AI-powered clinical drug trials to enabling preventative patient monitoring to wellness solutions such as wearables, the possibilities are endless. We've seen technology fill gaps in healthcare during the pandemic. Telemedicine apps are the first step toward making healthcare more equitable and accessible to all people, regardless of socioeconomic status. The widespread adoption of technology by both patients and healthcare professionals has enormous potential to improve the efficiency of public health entities. Advances in preventative health technology (such as wearables) can reduce overall healthcare costs by monitoring patients' status and detecting abnormalities earlier, allowing for faster response. Complex healthcare systems powered by AI analytics can more effectively distribute care and treatment etc.

Sustainable Future

A sustainable future balances environmental protection, economic growth, and social equity to meet present needs without compromising future generations. It relies on renewable energy, circular economies, responsible resource use, and climate action. Achieving it requires global cooperation, innovation, and policy changes to reduce emissions, waste, and inequality while preserving ecosystems.

- To reduce pollution
- To reduce energy consumption

- To reduce waste production and increase recycling capacity

Conclusion:

Science and technology are essential tools for creating a sustainable future. The goal of sustainability is to ensure that human activities do not undermine the capacity of ecosystems to meet people's needs, now and in the future. That's why we need new technologies and scientific knowledge to help us achieve our goals for sustainable development. Achieving a sustainable future will require innovation of new energy sources, materials, and infrastructure, as well as changes in how we produce food, travel, and build homes. In this blog, we will look at the impact of science and technology for a sustainable future.

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SCIENCE AND TECHNOLOGY: CATALYSTS FOR A SUSTAINABLE AND EQUITABLE FUTURE

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Abstract:

Science and Technology are vital for achieving a sustainable future by addressing global challenges like climate change resource poverty. They provide tools for sustainable management of the environment promote innovation and support economic growth while minimizing environmental impact. This Ideal explores how scientific advancements in various fields, including energy, agriculture and biotechnology can enable sustainable development. It also argues for enhancing scientific capacities, promoting open access to information, investing in education and researches crucial steps towards sustainable development. It highlights the transition from the Millennium Development Goals (MDGs) to the Sustainable Development Goals (SDGs), emphasizing the need for innovative and also it highlights the need for international cooperation, policy changes and equitable access to scientific innovation to ensure a more sustainable and prosperous future for all sectors of society.

Keywords: Millennium Development Goals, Sustainable Development Goals, Science and Technology, Sustainable Future.

Introduction:

Science and technology for a sustainable future help us understand our environment and our impact on it, which is essential for making smart decisions about how to use our resources. It can also help us find solutions to problems, such as climate change and pollution, and improve the quality of life for all people. Humanity of the third Millennium, have achieved incredible progress in technological, economic and political aspects which is reshaping our lives, but in spite of all these the world's foremost challenges are hunger and the exclusion of millions from basic health and education. As a response to this felt need of the hour, the leaders of the world came together at United Nations Headquarters in New York and the Millennium Summit 2000, as it was named, which was focused on making sure that the world becomes a better place to live in, where the global problems are eliminated. The historic Millennium Declaration committed nations to a new global partnership to reduce extreme poverty, and set out a series of 8-time bound targets, known as the Millennium Development Goals (MGDs). They are also known as Global Goals build on the MDGs. However, SGDs go much further than the MGDs, addressing the root causes poverty and the universal need for development that works for all people. It focusses on peace, prosperity, and wellbeing, and to preserve our planet. Sustainability and sustainable development have been defined in many ways, but the most frequently quoted definition is from the Report of the World Commission on Environment and Development "Our Common Future", also known as the Brundtland Report: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. (1)

Objectives

- To mention about the role of science and technology in sustainable future
- Impact of Science Technology on Sustainable Development
- To outline the areas in which science and technology contribute for sustainable future

Role of Science and technology in sustainable development

Science and technology are considered amongst the most effective means to enhance growth and socio-economic development of nations. Technological development has a profound and long-term impact on income distribution, economic growth, employment, trade, environment, industrial structure and defence and security matters. Science and technology for a sustainable future are likely to be one of the most important factors in determining whether humanity will succeed at tackling some of its greatest challenges: managing climate change; ensuring access to clean water; eliminating poverty; meeting health needs worldwide while protecting .The acquisition and use of science and technology (S&T) are critical for the achievement and sustenance of food security, as well as the promotion of public health and environmental quality.

The importance of science and technology to modern societies, and the role of a technologically educated population in promoting social and economic development, has long been recognized at the same time, 'modernization', if not properly managed, can exacerbate risk and its unequal social and geographical distribution can also widen disparities in personal incomes and well-being. The scientific and technological community can make a leading contribution to tackling major problems, such as fighting disease; overpopulation and urbanization; the digital/information divide and the impacts of information technology systems on world financial markets; coping with climate change; confronting the water crisis; defending the soil; preserving forests, fisheries and biodiversity; trade in biotechnological products and building a new ethic of global stewardship.

The universalism of science, and the globalisation of technological production and trade, offer unprecedented opportunities for focused cooperation by scientists and engineers, and the institutions that employ them, to further progress on SD. The complex relationship between the economy, society and the environment and scientific knowledge requires a multi-disciplinary approach, and calls for skilled communication to be able to address technological issues as well as the political framework within which problem solving necessarily takes place. At all levels, the role of science and technology is crucial; scientific knowledge and appropriate technologies are central to resolving the economic, social and environmental problems that make current development paths unsustainable. (2)

Impact of Science Technology on Sustainable Development:

A sustainable future balances environmental protection, economic growth, and social equity to meet present needs without compromising future generations. It relies on renewable energy, circular economies, responsible resource use, and climate action. Achieving it requires global cooperation, innovation, and policy changes to reduce emissions, waste, and inequality while preserving ecosystems, Different views on resources and economic growth have been put forward in the course of human history. The basic model of economic growth says that the factors of production are vital for economic growth.

Thus, GDP growth depends on capital growth and labour force growth. Up to now, capital accumulation and population growth have triggered economic growth. Industry. however, will decrease the demand for low-skilled workers. There several other factors affecting the productivity of these are several other factors a scale. The economic growth of countries depends on various affecting the productivity of these factors, such as technical progress, innovation, economies of factors; they can include demographic trends, political system, legislation, culture, trade relations, natural conditions, etc. The United Nations defines sustainable development to mean "meeting the needs of the present without compromising the ability of future generations to meet their own needs." (3)

The sustainability requires us to protect both natural resources and human health while using our available resources efficiently. In addition, it is an important driver of applied science and research in Slovakia and the improvement of workplaces for scientists. Smart industry also focuses on smart raw material and resource solutions in line with the sustainable development goals. Humans will perform creative activities whereas physically demanding work will be shifted from people to machines and systems, more decent working conditions will be created for employees.

Sustainable technologies would be one capable of meeting 'needs' using only a fraction—less than a tenth and maybe only a fiftieth—of the 'eco-capacity' used by today's technologies. Eco-capacity was, itself, introduced as a concept to describe the constraints on the permissible level of resource consumption, ecosystem disruption and pollutant emission that would be consistent with maintaining a stock of environmental capital and a stream of environmental benefits for the use of future generations. The sustainable technology development programme was established with the ambition of bringing about fundamental changes in innovation practices. People are cautious about using technology to solve problems perceived as outcomes from technological innovation. As a process, eco-restructuring implies achieving wide-ranging changes in societies and economies including, especially, a restructuring of production and consumption patterns both in amount and type. The economic status of the Netherlands is made possible by an intensive economy backed by high volumes of import, export, transport and value-adding industry. (4)

Sustainable Future

A sustainable future involves ensuring that current development meets the needs of the present without compromising the ability of future generations to meet their own needs. It's a holistic approach that integrates environmental, social, and economic aspects for a growing world. Creating knowledge and understanding through science equips us to find solutions today's acute economic, social an environment challenge and to achieving sustainable development and greener societies.

1. Environmental Sustainability:

- Resource Management: Efficiently using and conserving natural resources like water, land, and energy.
- Pollution Reduction: Minimizing pollution from various sources to protect air, water, and soil.
- Climate Change Mitigation: Reducing greenhouse gas emissions and adapting to the impacts of climate change.

2. Social Sustainability:

- Poverty Reduction: Working towards eliminating poverty and improving living standards for all.
- Equality and Inclusivity: Ensuring equal opportunities and rights for all, including marginalized groups.
- Social Justice: Addressing inequalities and promoting a just and equitable society.

3. Economic Sustainability:

- Sustainable Economic Growth: Promoting economic growth that is environmentally and socially responsible.
- Fair Labor Practices: Ensuring fair wages, working conditions, and social security for all workers. (4)

Conclusion:

The integration of science and technology is pivotal for achieving a sustainable future; asit provides innovative solutions to pressing global challenges such as climate change, poverty, and resource management. The United Nations emphasizes that advancements in science and technology are essential for implementing the Sustainable Development Goals (SDGs), enabling societies to develop sustainable practices while improving the quality of life for all. Moreover, Sustainable development is imperative to meet the needs of present generation without compromising the ability of future generations to meet their own needs. It requires integrating economic, social, and environmental considerations into all decision-making processes. Practicing sustainability starts with individuals adopting eco-friendly habits like saving resources, reducing waste, and using public transport.

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DIGITAL ARCHIVES AND PRESERVATION: TECHNIQUES FOR REVITALISING ENDANGERED LANGUAGES

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Abstract:

In the field of linguistic preservation, the integration of digital archives with artificial intelligence (AI)-based tools presents a transformative approach to revitalising endangered languages. Building on the works of Bird *et al.* (2009) and Krafft & Kusters (2016), this study explores the development of a sophisticated digital archive augmented with AI capabilities to enhance language documentation and revitalisation. The research centres on creating a comprehensive repository for storing, managing, and disseminating linguistic materials—such as audio, text, and video—pertinent to endangered languages. Central to this approach is the incorporation of AI-driven tools for language analysis, including tokenisation and text processing, which ensure accuracy and efficiency in linguistic documentation, as highlighted by Krauss (1992) and Lewis & Simons (2010). The methodology involves preparing data for training AI language models, emphasising the inclusion of endangered language-specific tokens, dialects, and idiomatic expressions (Clyne, 2003; Bhuvaneswari, 2022). The ultimate objective is to support preservation and revitalisation through accessible language learning tools and community-based participation. The study critically evaluates the role of AI and digital infrastructure in fostering linguistic diversity and cultural continuity, drawing on the insights of Robinson & Yip (2017) and Harrison (2020). Overall, this research underscores the potential of AI to contribute meaningfully to scalable, sustainable language preservation initiatives.

Keywords: Endangered Languages, Digital Archives, Language Revitalisation, AI in Linguistics, Language Preservation Techniques

Introduction:

Contextualising Endangered Languages

The revitalisation of endangered languages, which are vital to the world's cultural heritage, necessitates an understanding of the intricate cultural, social, and historical contexts that shape their vitality (Bhuvaneswari, 2022). These languages are more than tools for communication; they encapsulate the identities, values, and worldviews of the communities that speak them. Revitalisation efforts must therefore address the overwhelming influence of dominant languages and globalised cultural norms (Harrison, 2020). Effective strategies should emphasise the integration of endangered languages into everyday life, including cultural events, educational curricula, and social practices, to reinforce their relevance and encourage intergenerational transmission.

This cultural integration acts as a counterbalance to forces such as urbanisation, migration, and formal education systems that often marginalise minority languages (Lewis & Simons, 2010). Promoting the language in contexts like media, commerce, and community interactions can increase its visibility and appeal, especially among youth. Moreover, examining the historical trajectory of these languages—including oral traditions, archival records, and community narratives—can inspire renewed engagement and a collective sense of responsibility for preservation (Krauss, 1992). This historical grounding transforms language revitalisation from a purely academic endeavour into a culturally resonant movement.

Ultimately, successful preservation depends on adapting initiatives to the unique sociolinguistic realities of each community. Such a tailored approach respects the linguistic and cultural nuances essential for maintaining the integrity and resilience of endangered languages (Bhuvaneswari, 2022).

Digital Archives: A New Frontier in Language Preservation

Digital archives have emerged as a transformative force in the preservation of endangered languages, offering comprehensive, scalable solutions to safeguard the world's linguistic heritage. These technologically advanced repositories facilitate the digitisation, organisation, and long-term preservation of linguistic data, including historical texts, oral narratives, and multimedia content. By supporting intentional learning and deeper cultural understanding, digital archives not only conserve language materials but also help revitalize the cultural contexts in which these languages exist.

One of the key strengths of digital archives lies in their capacity to manage vast volumes of data efficiently. They provide structured, searchable access to diverse linguistic resources, thereby fostering interdisciplinary collaboration among linguists, anthropologists, educators, and technologists. These platforms also support educational initiatives by making endangered language materials accessible for curriculum development and community learning programs.

However, the adoption of semantic web technologies and linked data frameworks introduces complex challenges related to data access, privacy, and ownership. Questions regarding who controls archived content and how it is accessed must be carefully addressed, especially when working with Indigenous and minority language communities. Ethical considerations are paramount to ensure that these archives serve the interests of the communities they aim to represent and support.

Despite these challenges, digital archives hold significant cultural and educational value. They contribute not only to the preservation of literary and linguistic traditions but also to the creation of new forms of cultural and artistic expression. Accessibility issues, including inconsistent metadata standards and varying levels of technological infrastructure in different regions, remain ongoing barriers. Addressing these concerns requires inclusive design and sustained collaboration with community stakeholders.

Collaborative initiatives such as the Cherokee Language Digital Archive exemplify the importance of involving native speaker communities in the curation and maintenance of digital repositories. Similarly, the integration of university-based institutional repositories and emerging technologies like blockchain offers promising pathways for enhancing the security, traceability, and longevity of digital linguistic records.

Ultimately, digital archives serve as both preservation tools and platforms for cultural engagement, offering new avenues for exploring and appreciating the richness of the world's linguistic diversity. By bridging technology and tradition, these archives play a crucial role in ensuring that endangered languages are not only documented but also actively revitalised for future generations.

Scope and Significance of Preservation Techniques

Preserving endangered languages is vital for sustaining both linguistic and cultural diversity. Language loss represents more than the disappearance of a communication system; it entails the erosion of worldviews, oral traditions, and identity. Thus, the scope of preservation extends beyond mere documentation to encompass the revitalisation of language use within everyday life and intergenerational transmission.

Contemporary preservation efforts involve a range of strategies, including the systematic collection of audio-visual materials, transcription and translation of oral texts, and the promotion of language instruction through community-based and formal educational programs. These methods aim not only to preserve linguistic artifacts but to reintroduce endangered languages into domains where they have declined—such as homes, schools, media, and public life.

Digital archives and AI-based tools have become essential in these efforts by enabling the preservation, analysis, and dissemination of primary linguistic data. These technologies enhance accessibility and scalability, offering new ways to teach and learn endangered languages. Nevertheless, it is important to recognize that not all digital archives are designed with revitalisation in mind. Some serve primarily as repositories for academic research and may lack features that support community engagement or practical language learning.

The integration of artificial intelligence—particularly in language learning applications—has shown promise in facilitating early exposure, personalized learning, and sustained interest in endangered languages. However, the deployment of such tools must follow a needs-based approach, tailoring technological solutions to the sociolinguistic and cultural realities of specific language communities. Flexibility and adaptability are critical to the success of any revitalisation program.

Furthermore, improving the usability and relevance of digital collections is essential to ensure they serve revitalisation goals. This includes addressing issues such as user interface design, metadata comprehensibility, and language accessibility for non-specialists. As highlighted by Mirza (2017), collective intelligence-based systems—wherein community members collaboratively contribute to language documentation and learning—offer innovative pathways for participatory language preservation. These systems foster community ownership, enhance resource quality, and strengthen the social dimension of language revitalisation.

Aims and Objectives of the Study

The primary aim of this study is to develop a robust digital archive integrated with artificial intelligence (AI) to support the revitalisation of endangered languages. This involves designing and implementing a comprehensive digital repository capable of storing, managing, and providing access to diverse language-related resources, including audio, textual, and video materials.

The specific objectives of the study are as follows:

1. **To construct a centralised digital archive** that serves as a repository for endangered language materials, facilitating long-term preservation and public accessibility.
2. **To integrate AI-driven tools** for in-depth linguistic analysis, including tokenisation, morphological parsing, and syntactic structuring, thereby improving the accuracy and completeness of language documentation.
3. **To support language revitalisation efforts** through the development of accessible, AI-assisted language learning resources tailored to community needs.
4. **To foster community engagement** in language preservation by promoting participatory archiving and collaborative content development.
5. **To critically evaluate the effectiveness** of digital archives and AI tools in promoting linguistic diversity and cultural preservation.
6. **To contribute a scalable and sustainable model** for digital language preservation that can be adapted across various linguistic and cultural contexts.

By achieving these objectives, this study aims to demonstrate the transformative potential of AI and digital archiving in enhancing the preservation and revitalisation of endangered languages, thereby making a meaningful contribution to the broader field of linguistic and cultural preservation.

Historical Overview of Language Endangerment

Language endangerment has emerged as a pressing concern in the 21st century, posing the risk of irreversibly losing unique human knowledge systems, worldviews, and cultural expressions. As noted by Gorenflo *et al.* (2012) and Roche & Tsomu (2018), language extinction not only erodes linguistic diversity but also undermines the cultural identity and heritage of speaker communities. Driven by factors such as economic globalisation, rapid urbanisation, and the systemic marginalisation of minority languages, current projections estimate that between

50% and 90% of the world's languages may vanish by the end of this century (Maffi, 2005; Lee *et al.*, 2022).

This crisis is not confined to linguistics alone—it intersects with broader ecological and cultural concerns. Language loss often parallels declines in cultural and biological diversity, indicating a deep interconnectedness between linguistic heritage and the environments in which languages evolve (Hildebrandt, 2018; Gorenflo *et al.*, 2012). The disappearance of a language frequently entails the loss of traditional ecological knowledge, oral literature, and community-specific worldviews.

In response, numerous academic and policy-oriented efforts have emerged to combat language endangerment. Educational programs now focus on language documentation, revitalisation, and the sociocultural, economic, and political factors contributing to language decline (Sharma, 2021). Alongside these efforts, technological interventions—including computational modelling and artificial intelligence—are increasingly employed to analyse patterns of language shift and predict vulnerability to extinction (Koreinik, 2011). These tools highlight the interdisciplinary nature of the field, bridging linguistics with data science, anthropology, and environmental studies.

Additionally, recent scholarship has examined how agency is portrayed in discourses on language endangerment, calling attention to the roles of communities, institutions, and policymakers in shaping outcomes. This has led to a recognition that effective revitalisation strategies must be context-sensitive and community-driven.

In conclusion, language endangerment is a complex and multifaceted phenomenon, requiring interdisciplinary strategies that account for the linguistic, cultural, and ecological dimensions of language loss. The projected disappearance of a substantial proportion of the world's languages by century's end underscores the urgent need for innovative, inclusive, and sustainable preservation efforts.

Development and Evolution of Digital Archiving

Digital archiving has become a cornerstone of modern language revitalisation strategies. As digital repositories have evolved, they have significantly influenced how linguistic data is collected, stored, accessed, and disseminated. Evaluating the development platforms used to create language archives is essential to identifying tools that best support the preservation of endangered languages (Bharti & Singh, 2022). The adoption of open-source solutions, such as ArchivesSpace, reflects an ongoing evolution in archiving technology, allowing for flexible, community-adapted implementations (Sarkar & Biswas, 2020).

Community-centred approaches, exemplified by the Cherokee Language Digital Archive, underscore the importance of involving speaker communities in the creation and maintenance of archives. These participatory models ensure that the archive remains culturally relevant and useful for revitalisation efforts (Snead, 2023). Simultaneously, institutional perspectives on digital preservation—such as those explored by Ismail and Affandy (2018)—highlight the importance of continually adapting strategies to ensure long-term access to digital resources.

Moreover, sustainability in digital preservation remains a core concern. Burda and Teuteberg (2013) stress the necessity of aligning technological innovation with practices that maintain the accessibility of digital archives over time. Together, these developments signal a dynamic and responsive field, shaped by technological progress, community needs, and archival best practices.

Preservation Techniques: Past and Present

Preservation techniques for endangered languages have transitioned from traditional documentation methods to more technologically integrated models. Digital archives now serve not only as repositories but also as platforms for education, cultural exchange, and community engagement. Initiatives such as SiDHELA—India's first endangered language archive—demonstrate innovative, region-specific solutions tailored to the preservation of linguistic diversity (Narayanan, 2020).

The demand for trusted digital repositories has also intensified, reflecting a growing awareness of the need for reliable, long-term storage solutions (Ferreira *et al.*, 2021). Within academic settings, institutional repositories offer scalable solutions, with Vann (2021) highlighting best practices in information architecture and retrieval that enhance access for researchers and communities alike.

Collaboration with indigenous and local communities remains a critical element. Burke (2021) emphasizes that enriching archives with ethnographic context leads to deeper, more authentic linguistic records. Moreover, studies by Burke & Zavalina (2019, 2020) explore how free-text metadata and effective organisational structures within language archives can greatly impact usability and information richness.

In recent years, the integration of documentation and revitalisation—particularly through digital language applications—has shown promising potential. Little (2017) identifies these tools as means of reintroducing endangered languages into everyday use, particularly among younger generations. Parallel to this, the sociolinguistic study of attitudes toward endangered languages (Heinrich, 2015) informs policy and educational efforts, reinforcing the importance of culturally sensitive revitalisation strategies.

Gap Analysis in Current Research

Despite notable advancements, several research gaps persist in the domain of digital archiving for language preservation. One major gap lies in the limited research on effective community involvement strategies. While community-based models are widely endorsed, practical frameworks for sustained collaboration in archive development remain underexplored (Burke, 2021).

Additionally, the accessibility and usability of digital archives for non-expert users require further attention. Archives are often designed for linguistic researchers, leaving out broader community members who might benefit from or contribute to these repositories (Burke & Zavalina, 2019). Bridging this usability divide is essential for increasing community participation and archive effectiveness.

Emerging technologies, such as language learning apps, show great promise but are still under-investigated in the context of endangered languages. Little (2017) suggests these tools can connect users with languages in engaging, interactive ways, but more empirical research is needed to assess their efficacy and scalability.

Further, long-term preservation strategies remain a challenge, particularly in the face of rapid technological obsolescence and evolving digital standards (Ferreira *et al.,* 2021). Research into sustainable models for digital preservation—both technical and financial—is crucial.

Finally, issues related to policy and funding support have not received adequate scholarly attention. Comprehensive frameworks for policy-making and sustainable investment in digital archiving infrastructure could significantly enhance revitalisation outcomes.

Addressing these research gaps will strengthen the capacity of digital archives to function not only as repositories of endangered languages but also as active tools for revitalisation and cultural continuity.

Methodological Framework:

Design and Strategy of the Study

This study adopted a qualitative research methodology grounded in an interpretive perspective, emphasising the importance of cultural context, participant perspectives, and the co-construction of meaning. Central to the research design was the use of participatory observation techniques within indigenous language communities, allowing for authentic engagement with native speakers and culturally embedded practices (Figure 1 illustrates the methodological framework).

The data collection strategy integrated direct community involvement, fostering collaborative knowledge production and ethical engagement with language speakers. Audio recordings of native speech were captured during interviews, storytelling sessions, and communal events, ensuring naturalistic and context-rich data. To process and analyse the collected linguistic data, the study employed advanced linguistic software tools such as ELAN (EUDICO Linguistic Annotator) and FLEx (FieldWorks Language Explorer). These tools facilitated accurate data annotation, segmentation, and lexical database development, enhancing the precision and retrievability of the archived material.

Building on the work of Ellery *et al.* (2018), the study implemented structured training programs for community collaborators, followed by post-training assessments to ensure data reliability and fidelity. This structured approach improved the accuracy of observational and linguistic data collected by community members ("Using Community Members to Collect Observational Data: Observer Training and Data Quality Assessment," 2018).

Qualitative data collection was further enriched through focus groups and key informant interviews, as advocated by Smylie, Kaplan-Myrth, and McShane (2009). These methods provided in-depth insights into language use, transmission patterns, and sociolinguistic attitudes in indigenous settings ("Indigenous Knowledge Translation: Baseline Findings…").

Incorporating transnational perspectives into the methodology, as suggested by Whiteside (2013), allowed the research to consider the mobility and multilingual negotiation of indigenous speakers, especially in diasporic or urban contexts. Meanwhile, Evans *et al.* (2009) underscored the importance of combining indigenous methodologies with participatory action research to ensure that research outcomes are both community-relevant and methodologically rigorous ("Common Insights, Differing Methodologies").

Collectively, these methodological choices underline the study's commitment to community empowerment, methodological rigour, and technological integration. By aligning with both indigenous knowledge systems and best practices in linguistic documentation, the study effectively captures the complex dynamics of language use and preservation in endangered language communities.

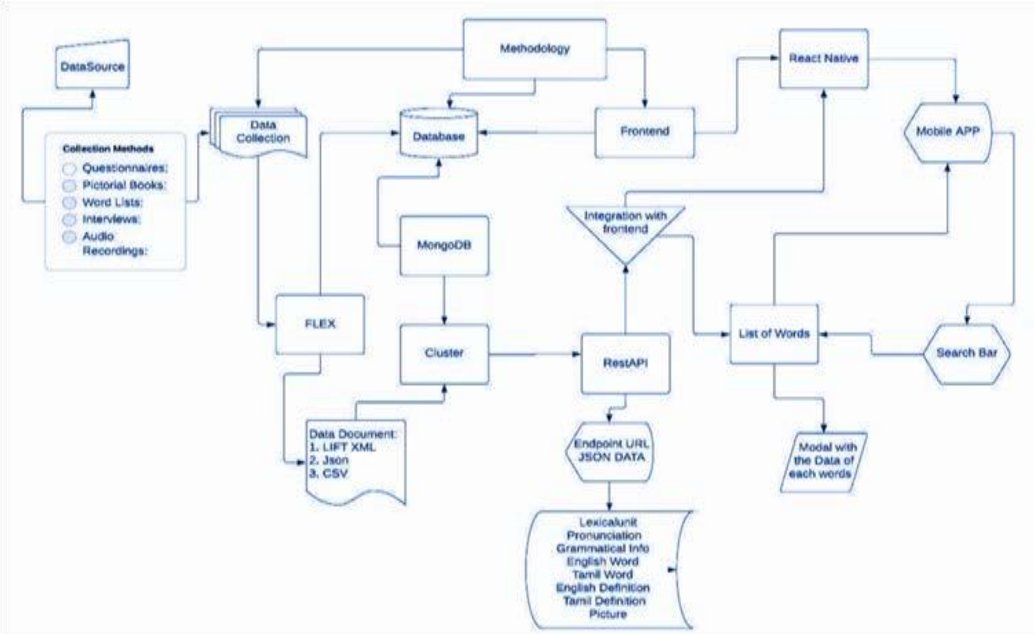

Fig. 1: Unified Model Language (UML) Diagram

Data Acquisition and Processing

The integration of advanced Natural Language Processing (NLP) technologies and AI-based tools has become indispensable in the ongoing efforts to preserve and revitalise endangered languages. This study deployed a comprehensive, NLP-driven language preservation system, leveraging a newly developed NLP model specifically adapted to address the unique linguistic challenges posed by endangered languages (see Figure 2).

At the core of this system lies a robust capability for text tokenization and linguistic analysis, which are foundational processes for accurate documentation and digital preservation. As emphasised by Bird *et al.* (2009) and Krafft & Kusters (2016), tokenization is critical for parsing language data into analyzable units, thereby enabling detailed morphological and syntactic analysis—an essential function when working with languages that lack standardized orthographies or digital presence.

The data acquisition phase involved collecting linguistic materials in audio, textual, and transcribed forms, drawn from community recordings, oral narratives, and historical texts. Once gathered, this data underwent a meticulous preprocessing phase to prepare it for AI model training. This phase focused on:

- **Endangered language-specific tokens**, which encapsulate phonetic and grammatical structures unique to lesser-studied languages.
- **Regional dialect tokens**, which help account for local linguistic variations and ensure inclusivity across dialectal diversity (Lewis & Simons, 2010; Fishman, 1991).
- **Idiomatic expressions and culturally embedded phrases**, essential for conveying the richness of a language's oral traditions, metaphors, and worldview (Harrison, 2020).

These targeted linguistic units were not only essential for building robust AI models but also critical for ensuring cultural fidelity in the digital representations of endangered languages.

The NLP model was trained iteratively with feedback loops and community validation to refine output quality and accuracy. The processed data was then fed into the digital archive, making it accessible for both linguistic research and educational applications. This AI-enhanced pipeline thus enables a scalable, sustainable, and culturally sensitive approach to language preservation, demonstrating how technology can meaningfully support linguistic and cultural resilience.

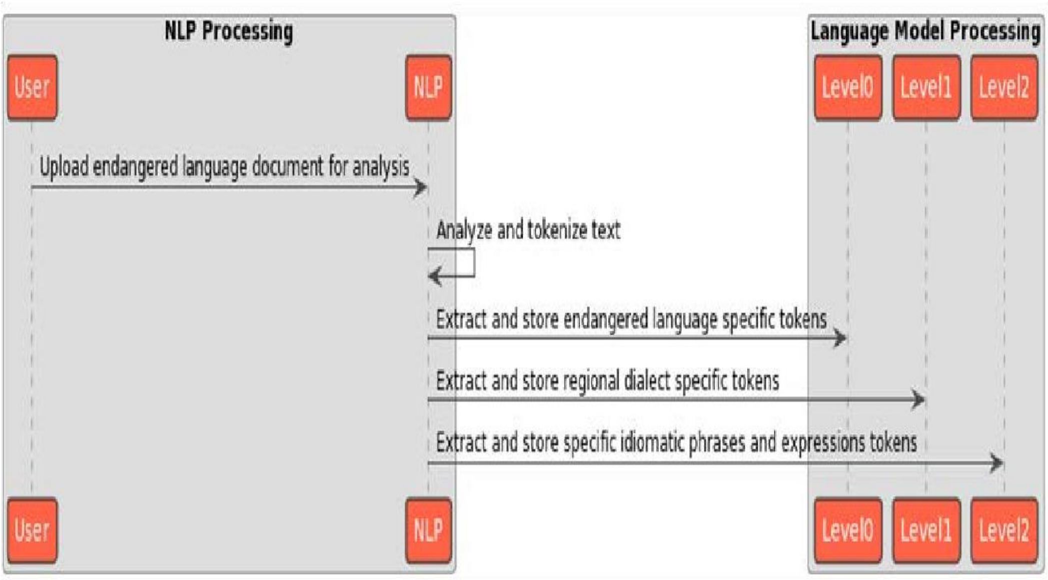

Fig. 2: Language Model Processing

Following data preparation, the language model training process commenced. Each level of the language model – Level 0 (Foundation Model), Level 1 (Regional Dialect Model), and Level 2 (Idiomatic Phrase and Expression Model) – is carefully trained to capture the respective features of the endangered language, its regional dialects, and idiomatic expressions (Clyne, 2003; Bhuvaneswari, 2022). This hierarchical training approach ensures a comprehensive understanding and preservation of diverse forms of language.The system is essential for updating AI models, which are critical for optimising language models. This step integrates new findings or insights from text analysis and processing stages, ensuring that AI models remain current and effective in language preservation efforts (Robinson & Yip, 2017).

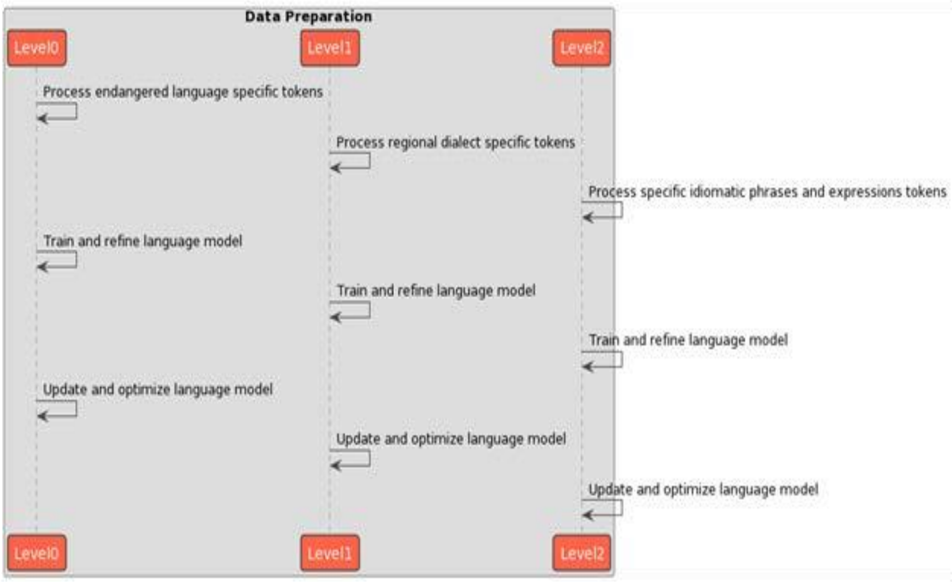

Fig. 3: Data Processing

Tools and Techniques in Digital Archiving

Digital archiving employs a suite of tools and methodologies designed to ensure the secure management, long-term accessibility, and integrity of digital data. These tools are essential in mitigating potential threats such as data degradation, technological obsolescence, and unauthorized access. Within the context of endangered language preservation, digital archiving becomes a strategic framework combining technological innovation with community-driven practices. This framework is comprised of several interrelated components, described in detail below:

- **Data Collection and Storage**

  This foundational component involves the systematic collection and management of multimedia data related to endangered languages. It includes the gathering of audio recordings, video interviews, written texts, and transcriptions, often sourced through fieldwork and participatory research within indigenous communities.

- **Digital Language Archive**
  Serving as the core repository, this component ensures the long-term, secure storage of language documentation. The archive is structured to accommodate diverse data types and is designed to comply with international standards for digital preservation.
- **Accessibility**
  The digital archive is structured for open and equitable access by researchers, educators, language community members, and the general public. By prioritising accessibility, the archive contributes to inclusive knowledge sharing and intergenerational language transmission.
- **Usage and Access Policy**
  A clearly defined policy governs the ethical use, data rights, and privacy considerations related to archived materials. It ensures responsible engagement with culturally sensitive data and protects the intellectual property of language communities.
- **Language Documentation**
  This module supports detailed documentation through the use of automatic transcription tools, morphosyntactic analysis, and metadata tagging. It also includes the creation of grammars, dictionaries, and language learning resources, which are integral for revitalisation efforts.
- **Collaboration with Local Communities**
  A cornerstone of this framework, this component emphasises active partnerships with indigenous and local language speakers. Community members are engaged not only in data collection but also in reviewing, curating, and contextualising archived materials, ensuring cultural relevance and authenticity.
- **Technological Advancements**
  The integration of AI and machine learning technologies enhances the efficiency of data processing, including automated transcription, text analysis, and pattern recognition. These tools expand the scope and scalability of language preservation activities.
- **Training and Support**
  To ensure sustainability, the framework includes structured training for both archive depositors and end-users. This includes guidance on metadata creation, file formats, preservation strategies, and data retrieval methods, empowering communities and researchers to engage with the archive effectively.

Together, these components form a holistic and scalable model for digital archiving in endangered language preservation. The process begins with Data Collection and Storage, followed by secure preservation in a central Digital Language Archive. Components such as Accessibility, Usage Policies, and Community Collaboration ensure ethical, inclusive, and culturally respectful engagement with archived materials. Technological integration and capacity-building initiatives further enhance the robustness and future-readiness of the archive, positioning it as a vital resource in the global effort to revitalise linguistic diversity.

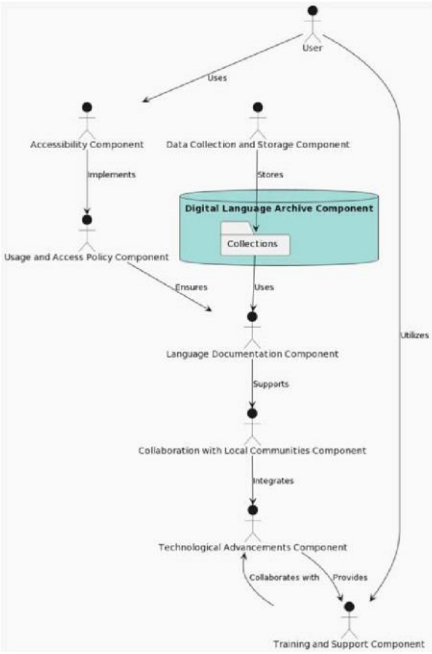

Fig. 4: Digital Archive Framework

Collaboration contributes to its cultural relevance and sensitivity. The role of Technological Advancements is to enhance the archive's capabilities, and Training and Support are provided to ensure effective utilisation and sustainability.

Conclusions:

This research marks a significant advancement in the field of linguistic preservation, highlighting the transformative potential of integrating digital archives with AI-based tools. Digital archives have evolved beyond their traditional role as static repositories to become dynamic platforms that facilitate deeper understanding, engagement, and appreciation of the world's linguistic diversity.

The integration of Natural Language Processing (NLP) and Artificial Intelligence (AI) technologies has opened up innovative avenues for the documentation, analysis, and revitalisation of endangered languages. These technologies support scalable solutions for language learning, data processing, and cultural preservation—ensuring that endangered languages remain accessible to both current and future generations, as well as to researchers worldwide.

This study underscores the critical importance of continued innovation and interdisciplinary collaboration in the realm of language preservation. The synergy between cutting-edge technologies and established archival practices offers a robust and adaptable model for safeguarding linguistic and cultural heritage. However, the success of such models depends on addressing persistent challenges, including usability, accessibility for non-expert users, and ethical concerns related to data ownership and community consent.

These findings align with the perspectives of Cushing & Osti (2022) and Borgman, Scharnhorst, & Golshan (2018), who emphasise the need for a nuanced and responsible application of technology in the humanities and social sciences. The study makes a significant contribution to the field by offering actionable insights and outlining future research directions in digital archiving and AI-assisted language revitalisation.

In conclusion, this research advocates for a balanced approach—one that blends technological advancement with a deep understanding of the social, cultural, and ethical complexities of language preservation. Such an approach ensures that digital innovations meaningfully contribute to the ongoing global efforts to protect and revitalise our shared linguistic heritage.

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HARNESSING SCIENCE AND TECHNOLOGY FOR A SUSTAINABLE FUTURE

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Abstract:

The article presents the role of science and technology in fostering a sustainable future. It helps us understand our environment and our impact on it, which is essential for making smart decisions about how to use our resources. It focuses on how scientific and technological advancements can contribute to sustainability in various aspects of life. Also focuses on the key areas of sustainable developments and scientific contributions. Advancing a Nation's capacity in science, technology and innovation and its application in economic activities are essential factors for expanding people's capabilities and achieving sustainable development.

Keywords: Sustainable Development Goals, Science and Technology, Sustainable Future.

Introduction:

Science and technology for a sustainable future offer hope for a better tomorrow by allowing us to create sustainable solutions in every sector of society, from agriculture, transportation, and infrastructure development all the way up to smart cities. The goal of sustainability is to ensure that human activities do not undermine the capacity of ecosystems to meet people's needs, now and in the future. That's why we need new technologies and scientific knowledge to help us achieve our goals for sustainable development.

Sustainability is a social goal for people to co-exist on Earth over a long period. Creating a sustainable world requires Interdisciplinary cooperation on the basis of disciplinary excellence. It should be based on a broad understanding of science, covering the whole range of disciplines from natural sciences to engineering to social sciences and the humanities. It should address the three dimensions of sustainable development- social, economic and environmental. The specific role of science for sustainable development goes beyond issues like technology transfer and must not be limited to that of a tool only. Science is central to the implementation of other goals. Scientific knowledge can support translation of targets to national policies and help measure and evaluate impact.

Science and technology influence society as never before. Scientific achievements continue to expand the frontier of knowledge. They increasingly contribute to technological progress that affects our ways of living and working. In order to reduce poverty and achieve sustainable economic growth, countries must establish new science and technology policies to create knowledge-based development.

Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains two key concepts within it:

- The concept of 'needs', in particular, the essential needs of the world's poor, to which overriding priority should be given.
- The idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs.

➢ **Science for sustainable future**

Science plays important role for sustainable future. Following are some methods which can plays role in sustaining future.

- **Scientific Research-** helps us understand the causes and impacts of climate change, allowing us develop effective adaptation strategies for sustainable future.
- **Scientific understanding**- of water cycles, ecosystems and biodiversity helps us manage resources sustainably and protect them from depletion.
- **Renewable energy technologies-** Such as solar, wind and geothermal are essential for reducing green house gas emission and transitioning to a low carbon economy which can sustain pollution free environment for long time.
- **Climate modeling-** helps us predict future climate scenarios and inform policy decisions to maintain sustainability.
- **Sustainable agriculture practices-** like crop rotation and integrated pest management can reduce environmental impact and enhance food security.
- **Green Chemistry and materials Science-**are crucial for developing sustainable products and processes that minimize waste and pollution.

Biotechnology is expected to bring important advances in medical diagnosis and therapy, in solving food problems, in energy saving, in environmentally compatible industrial and agricultural production, and in specially targeted environmental protection projects.

➢ **Technology for sustainable future**

Below listed are some developments which can help for sustaining future.

- **Artificial intelligence-** By using Artificial intelligence one can save the energy, time and manpower for a particular work, which helps for sustainable future.
- Artificial intelligence can be used to optimize resource use, improve energy efficiency and personalize health care.
- **Biotechnology-** It offers solutions for sustainable food production, renewable energy and environmental remediation.

- **Sustainable infrastructure**- Designs, such as Green buildings and smart cities can reduce energy consumption and enhance quality of life.

Technology can help make cities more sustainable by improving energy efficiency, reducing emissions, and enhancing mobility. Smart city technologies such as intelligent lighting, building automation, and traffic management can improve the quality of life for urban residents while reducing environmental impact.

In conclusion, technology will play an increasingly crucial role in achieving sustainability goals in the future. From renewable energy to sustainable agriculture, sustainable transport to waste management, water management to sustainable cities, technology offers solutions to some of the most pressing sustainability challenges we face. As we continue to develop and adopt new technologies, we must ensure that they are aligned with sustainability goals and contribute to a sustainable future for all.

➢ **Examples of science and technology for sustainable future**

Sustainable energy is the use of sources of energy that can be consumed without causing significant damage to the environment. There are several different types of sustainable energy as listed below.

1. Biotechnology-

It refers to the process of replacing polluting materials with sustainable alternatives. There for this type of technology helps us achieve sustainability. Biotechnology is uniquely positioned to replace polluting materials and chemical processes with more sustainable, biological alternatives.

The number of applications where biotechnology could make a difference towards sustainability is virtually unlimited. Here are 12 of the areas where biotech is already making an impact.

- Bio fertilizers- Chemical crop fertilizers are responsible for environmental pollution all around the world. A more sustainable alternative would be to replace them with bio fertilizers.
- Bio fuels- In recent years, bio fuels which are derived from organic sources such as biomass and organic waste, have become an increasingly common alternative for sustainable future.
- Bio pesticides- Current methods to get rid of dangerous pathogens use harsh chemicals that can pollute the environment and be toxic for humans, as well as other forms of life. Biotechnology could offer eco-friendly alternatives called biopesticides, which are derived from natural materials like animals, plants, bacteria, and certain minerals.

- Bio plastics- Plastic pollution is one of the major environmental issues we are currently facing. New products made from renewable biomass sources, known as bio plastic, could be the solution to this problem.
- Carbon capture- Carbon dioxide is the primary culprit responsible for global warming. Therefore, reducing the amount of carbon dioxide in the atmosphere is a key to averting the impending climate crisis. This is where carbon capture and storage comes into play, as it can be a vital tool to remove carbon dioxide from the atmosphere
- Clothing- Fast fashion is a big sustainability issue, and biotechnology could put a stop to its environmental impact by replacing polluting chemical processes and making textile waste recyclable and biodegradable
- Cultivated meat- The meat industry is a huge polluter. Biotechnology could significantly reduce the use of land, water, and energy by growing meat without the animal, directly from a small sample of muscle and fat cells
- Enzymatic detergents
- Flavouring - Most flavourings were traditionally extracted from plants. Today, however, many of them are produced through petrochemical processes. Biotechnology could provide an environmentally friendly alternative that does not require as much land and resources as traditional methods.
- Genetically modified crops
- Construction material
- Cosmetics

2. Smart mobility

- Smart City: A city that uses information and communication technology to improve the quality of life of its citizens.

Smart Mobility is the use of technology to enhance mobility in cities through a focus on interconnected transport systems and services for better mobility options. Such technologies can reduce travel costs, air pollution, and GHG emissions through which it helps for sustainable future.

3. Sustainable infrastructure

Replacing old urban infrastructure for new modern and sustainable elements will make cities more inhabitable and inclusive.

➢ **Use of resources for a sustainable future**

In a world where the term ‘sustainability’ is as common as ‘innovation,’ understanding how to truly achieve sustainable development is more critical than ever. In a world where the need for sustainable development has become increasingly urgent, embracing responsible practices is crucial. Here are 10 ways to achieve sustainable development where individuals, communities, and societies can contribute to this global goal. Everyone can help for sustainable future by using resources in following 10 ways.

1. **Embrace Renewable Energy**

Embracing these renewable energy alternatives lessens the environmental impact associated with fossil fuel extraction and combustion and promotes energy independence and sustainability.

2. **Promote Sustainable Transportation**

Embracing electric vehicles powered by renewable energy sources significantly reduces greenhouse gas emissions and dependence on fossil fuels. By promoting and supporting these sustainable transportation options, communities and individuals can actively contribute to improving air quality, reducing greenhouse gas emissions, and fostering a healthier, more sustainable environment for current and future generations.

3. **Practice Waste Reduction and Recycling**

Reducing waste and implementing recycling practices are pivotal steps in fostering sustainability. By adopting a waste reduction approach that includes recycling, reusing items, composting, and flavoring products with minimal packaging, individuals and communities contribute significantly to lessening their environmental impact.

Recycling materials such as paper, plastic, glass, and metal reduces the volume of waste sent to landfills and conserves resources by turning used items into new products. Additionally, reusing items and composting organic waste minimizes landfill contributions and enriches soil health for agriculture.

4. **Support Sustainable Agriculture**

Promoting sustainable agriculture involves championing local and organic farming practices and prioritizing environmental health and biodiversity. Organic farming preserves soil integrity, allowing for increased soil fertility, moisture retention, and long-term sustainability.

5. **Advocate for Conservation**

Advocating for conservation is a critical pillar in preserving the delicate balance of our planet. Protecting and restoring ecosystems, forests, and water bodies are fundamental to maintaining biodiversity and safeguarding natural resources. Forests, often termed the lungs of the Earth, play a pivotal role in mitigating climate change by absorbing carbon dioxide. By advocating for the conservation of these natural resources, we contribute to the well-being of our planet and future generations, which can help for sustainable future.

6. **Educate and Raise Awareness**

Education is essential for the sustainable and equitable use of biodiversity and its conservation. The future of biodiversity will depend on the global collective action of an educated society, including efforts to promote local and indigenous knowledge of biodiversity. Education on environmental issues and sustainable practices is a key.

7. **Promote Ethical Consumerism**

Opt for eco-friendly, fair trade, and sustainably sourced products. Support businesses that prioritize sustainability in their operations and supply chains.

8. **Empower Women and Girls**

Ensuring gender equality and providing women and girls access to education and healthcare can lead to more sustainable communities and economic growth.

9. **Invest in Innovation**

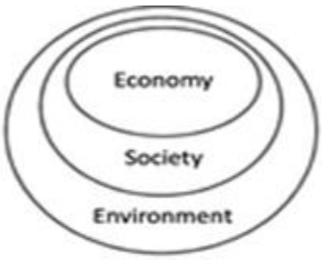
Supporting research and innovation in sustainable technologies and practices can lead to significant advancements in achieving environmental and social goals.

10. **Advocate for Responsible Policies**

Encourage governments and businesses to adopt sustainability policies, including regulations supporting renewable energy, emissions reduction, and environmental conservation.

➢ **The Three Pillars of Sustainability**

The three pillars of sustainability are a powerful tool for defining the *complete* sustainability problem. This consists of at least the economic, social, and environmental pillars. Maintaining sustainability in all the three pillars will give the sustainable future. If any pillar is weak then the system as a whole is unsustainable. Two popular ways to visualize the three pillars are shown.



One pillar is related to another by sustainability. Sustainability will be maintained by maintaining the conditions of economic, environment and social as follows.

Social Sustainability

Social sustainability is the ability of a social system, such as a country, family, or organization, to function at a defined level of social well being and harmony indefinitely.

Problems like war, endemic poverty, widespread injustice, and low education rates are symptoms a system is socially unsustainable.

Environmental Sustainability

Environmental sustainability is the ability of the environment to support a defined level of environmental quality and natural resource extraction rates indefinitely. By maintaining the environmental condition can help for sustainable future.

Economic Sustainability

Economic sustainability is the ability of an economy to support a defined level of economic production indefinitely. Economic sustainability entails evaluating the environmental impact of economic activity and devising sustainability goals to create a more livable future. Economic sustainability is a broad set of decision-making principles and business practices aimed at achieving economic growth without engaging in the harmful environmental trade-offs that historically accompany growth.

Conclusion:

Sustainable development meets present needs without compromising the future. It requires holistic, systems-thinking about environmental, social, and economic limitations. Also it requires integrating economic, social, and environmental considerations into all decision-making processes. Practicing sustainability starts with individuals adopting eco-friendly habits like saving resources, reducing waste, and using public transport.

We all have a role through our individual choices and actions. By working together to rethink and transform how we live and produce, we can build an equitable society that thrives within planetary boundaries.

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REVIEW ON ISOLATION OF FLUORIDE FROM *CAMELLIA SINENSIS* LEAF FOR FORMULATION OF TOOTHPASTE

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Abstract:

Tea leaf or *Camellia sinensis* are efficient at absorbing and accumulating fluoride from the soil and air, and it is mainly stored in leaves. The mature leaf has high amount of fluoride concentration of nearly 98% of plant fluoride concentrated in the leaves. Fluoride is widely recognized for its dental health benefits, particularly in the prevention of caries. Tea leaves especially green and black varieties, are known to contain significant amounts of naturally occurring fluoride. Fluoride strengthens the enamels of tooth, tooth decay could be decresaed and prevent from the bacteria growth. It was a mineral that's found in soil and rocks. It remineralizes tooth enamel and slows down the process of demineralization. It can reduce the risk of cavity by about 25%. The isolation of fluoride from tea leaves process may involves solvent extraction techniques, optimizing parameters such as temperature, time, and solvent type to maximize fluoride yield. Preliminary results indicated that the fluoride isolation from tea leaves was efficient, yielding a concentration suitable for dental applications. The formulated toothpaste demonstrated promising characteristics in terms of fluoride content, flavor, and texture, as well as antibacterial activity against common oral pathogens. This research highlights the potential of utilizing natural sources for fluoride incorporation in dental care products, promoting a sustainable approach to oral hygiene. The natural dental care solution of extracting fluoride from tea leaf for toothpaste formulation can promote the oral hygiene and also helps in environmental sustainability. Further studies are recommended to assess long-term efficacy and consumer acceptability.

Keywords: Fluoride, *Camellia sinensis*, Tooth paste, Dental Carries, Remineralization, ntibacterial activity.

Introduction:

Tea leaves have rich antioxidant content which is helpful in protecting against cell damage. The mature tea leafs have rich fluoride property, which helps in preventing tooth decay and it's also helpful in promoting oral health. The fluoride content from tea leafs has medicinal property to cure dental related problem. Fluoride is an anion present in various environment. Little amount of fluoride is vital in preventing dental carries [1].

Caries was a disease which causes imbalance when interacted with cariognic bacteria in dental plaque and carbohydrates (sugar). Regular brushing with toothpaste containing fluoride will prevent dental carries, according to the concentration of fluoride the preventive effect will differs[2]. Fluoride in toothpaste could be present in the form of Sodium Fluoride (NaF), Stannous Fluoride ($SnF^{2)}$ and Sodium mono fluorophosphate (Na_2PO_3F) of 0.1% with water fluoridation [3].

***Camellia sinensis* Leaf**

Tea is one of the most popular beverages in the world. It was an easily available plant source for the accumulation of fluoride. The mature tea leaf *Camellia sinensis* has the highest fluoride content when compared to other plants variety. The fluoride concentration in tea leaves was directly related to the maturity of the tea leaves at harvest. So, the leaf *Camellia sinensis* is used for the extraction of fluoride as a natural derivative for the formulation of toothpaste to prevent dental carries and also to strengthen tooth enamel [4].

Constituents of Toothpaste

Toothpaste constituents are specifically formulated to clean, protect and improve oral hygine. It typically includes a combination of several ingrediants, each serving a specific function. The primary constituents of toothpaste includes:

Table 1: Constituents of Toothpaste (Dan Kern., *et al.*, 2023)

Sr. No.	Materials	Amount (%)
1.	Fluoride	0.76%
2.	Abrasive	10-40%
3.	Metal ions	8-20%
4.	Surfactants	1-2%
5.	Arginine	2- 4%
6.	Enzymes	1-2%
7.	Humectants	0.3%
8.	Essential oils	20-70%
9.	Solvents	20-40%
10.	Carragenam	0.6-1.2%
11.	Gelling agents/ Binders	1-2%
12.	Flavouring agents	0.5-2%
13.	Colouring agents	0.1%
14.	Preservatives	00.5-0.5%

1. **Fluoride**

One of the most important discoveries in 1914 is the introduction of fluoride into the toothpaste formulation. Till 1960 the ADA have not approved the use of fluoride salts ine the toothpaste formulae. The regular use of fluoride through various source was extremely effective in preventing carious lesions. The carious lesion will result in demineralization or remineralization over certain time duration. To preventing carious lesions and to promote remineralization, the fluoride was used to slow down the demineralization [6].

The fluoride can reduce the risk of carious lesions and promotes to remineralize the enamel. In recent days there are certain formulas that contain fluoride, the fluorinated component of toothpaste could be present in the form of: Sodium Fluoride (SF), Sodium Monofluorophosphate (MFP), Stannous Fluoride (SnF_2), Amine Fluoride, Stannous Chloride, Aluminum Fluoride and etc. The toothpaste efficiency in preventing dental carries is mainly depending on the concentration of fluoride [7].

It could be without fluoride or with high fluoride concentration, upto 5000ppm, in that all formulas that contain more than 1500ppm Fluoride should be dispensed only on prescription and only for ages 10 and older, and also used in specific clinical settings. Fluoride bioavailability and exposure levels in tea infusions are also reviewed. Fluoride level, due to its narrow therapeutical range, must be constantly monitored in beverages, especially in daily-consumed plant infusions. Fluoride is important for prevention of tooth decay and dental related problems [8]. The fluoride could be present in the form of:

- **Sodium Fluoride (NaF):** It is generally known as the fluoride salt which is used in mouthwashes and toothpastes. This sodium fluoride (NaF) will provides the highly reactive fluoride ion and its formulation with a compatible abrasive is important [9].
- **Stannous Fluoride (SnF_2):** It is successfully applied in the formula of toothpaste in 1950, which benefits in protection against cavitity. By finding the abrasive substance with low reactivity with fluoride to succeed in maintaining the bioavailability of fluoride. The successful formula included 0.454% Stannous Fluoride and, as an abrasive, Calcium Pyrophosphate, was marketed as Crest® with Fluoristan®. Until 1990s the manufacturer did not develop method to stabilize the formula with Stannous fluoride, which helps in the prevention of carious lesions.
- **Sodium monofluro phosphate (MFP):** Sodium monofluro phosphate is an colorless and odorless and which is soluble in water. Usual MFP content in toothpaste is 0.76% and is used to replace the level of Sodium Fluoride mainly in baby toothpastes [10].

2. **Abrasives**

Abrasive substances uses in the toothpaste content has been recognized since antiquity using over time, various materials used include shell, marble dust, bone ash, and corals and pumice stone was used to remove food debris and stains on teeth. In order to ensure good mechanical cleaning on teeth 3 elements were needed:

1. Abrasive agent.
2. Thickening agent.
3. Surface active agent.

Abrasives was an insoluble substance, it includes Silica, Phosphates, Metal Oxides and Carbonates. The most used abrasive includes hydrated silica, hydrated alumina, calcium carbonate, calcium pyrophosphate, sodium metaphosphate, Nano hydroxyapatite, diamond powder and baking soda. The substance of abrasive is effective in cleaning tooth [11].

The compatibility of the abrasive agent with other components of the toothpaste, especially with the active substances like fluoride, and the acceptable formulation like viscosity and texture, and also without changing the important attributes for consumer for easier attraction-like taste and appearance of the toothpaste. Different abrasive agent and its clinical application on each tooth paste which may vary in each formula. Most widely used abrasives may involves Silica, Calcium phosphate, Sodium bicarbonate and Calcium Carbonate present in the amount up to 8-20%, and other abrasives like pertile and alumina could be present up to 1-2% in lower concentration because of their higher abrasiveness compared to enamel. Some abrasives could be taken in higher concentration which exceeding 50% due to their less abrasiveness [12].

a. **Calcium Carbonate:** Calcium carbonate was a white, fine, odorless, microcrystalline powder which is insoluble in water. Its abrasiveness is higher than the calcium phosphate so it can be used for the longer duration. There are two types of calcium carbonate, a heavy one and precipitated one. Heavy ones raw material was limestone and precipitated ones raw material was calcium hydroxide. When its binds to sodium fluoride as a result it will become ineffective like the anti-caries agent, even when if the toothpaste is formulated with sodium mono fluorophosphate [13].
b. **Calcium Phosphate:** Calcium phosphate is available in hydrate or anhydride form. The anhydride is in harsher form. But the hydrate has the abrasive effect and feels good to use. It has the good compatibiltity and neutral pH which will easily binds with other ingrediants. In toothpaste it loses its water of crystallization and changes to anhydride form which makes the toothpaste harsher. For that, magnesium salt or other stabilizing agent is added [14].
c. **Sodium Bicarbonate:** Sodium bicarbonate may belong to the category of abrasive substance in toothpaste composition, but it has the ability to reduce the pathogenic microbial flora and maintains the oral pH. It is also known to be baking soda, bicarbonate or the carbonic acid with mono sodium salts. Baking soda has the compatibility with sodium fluoride and have the stability to possess both mechanical and biological action and

influence the Stephen curve, and prevents carries lesions with their buffer capacity in which pH returns back to normal even after the ingestion of carbohydrates [15].

d. **Silica**: In the fluoride containing toothpaste silica play a vital role, because when reacting it does not form any insoluble salt. Because of its refractive index it forms a clear gel in the composition of toothpaste when compared to other abrasive substance index [16].
e. **Other abrasive substances:** Other abrasive substances like magnesium carbonate, calcium pyrophosphate, insoluble sodium meta phosphate could be used. Alternative for dibasic calcium phosphate the aluminum hydroxide could also be used [17].

3. Metal-ions:

The most commonly used metal ions in toothpaste may involves Zinc (Zn_{2+}) and Stannous (Sn_{2+}). These metals can limits the bacterial growth, inhibits the plaque formation and the glycolytic sequence of oral anaerobic bacteria inhibit plaque formation and the glycolytic sequence of oral anaerobic bacteria and restricts the ability of bacteria that being converted from urea to ammonia. And also reduces the bacterial colonies in dental surfaces [18].

a. **Stannous-Ions:** It could be present in the form of stannous fluoride or stannous pyrophosphate. It has both bacteriostatic and bactericidal action by inhibiting the subsequent activity of the bacteria. In combination with fluoride, it inhibits both the demineratization of dental hard tissues and prevents inflammation caused by bacteria [19].
b. **Zinc-Ions:** It is an essential element which is ubiquitous in life forms. It has the higher antimicrobial property. Zinc based toothpaste will reduces the effects of bacteria in oral bio-film preventing and controls the plaque, halitosis, gingivitis and also prevents the formation of calculus. In tooth paste Zinc could be present in the form of zinc chloride or zinc citrate. Toothpaste which contains both zinc and fluoride in combination will decrease demineralization and promotes remineralization when compared to the toothpaste with only fluoride contents [20].

4. Surfactants:

The surfactants are the foaming agents which have the function on dispersing in the oral cavity. The surfactants have the ability of dispersing, foaming, suspending, permeability and cleaning qualities. It may lower the surface etension of liquid medium in the oral cavity, to make more contact with teeth easily and it may penetrate and dissolves easily. The surfactants also have the function to dispense the flavors in tooth paste [21]. The most commonly used surfactant is:

- **Sodium Lauryl Sulfate (SLS):** Some studies says that SLS may be allergic to skin and mucosal layer damaging them by glycoprotein denaturation, so it is no suitable for all age groups, particulatarly for elders because the amount of salivary secretion at that age could be diminished. If the use of SLS containing toothpaste is higher it could increase the risk of Recurrent foot and mouth ulcer [22].

5. Arginine

It could be known as both Arginine or L-Arginine, It was an unique, semi essential amino acid which is composed of both proteins and peptides which plays an independent role in the controlling of biofilm. It is also involved in physiological process within oral cavity and prevents dental diseases. By altering the mechanism of bacterial plaque, it will prevent the carries lesions. Depending on the arginine concentration it will destabilizes the biofilm, but does not show any bacteriostatic or bactericidal property [23].

Its main role to, modulate the metabolism of bacterial plaque and increasing the pH by producing ammonia. The higher concentration of Arginine is 2-4% in 5% NaF could vanish the potential to modulate the biochemical composition of bioflim that develops at the tooth enamel [24].

6. Enzymes:

The salivary components represented by enzyme and protein contribute to the production against pathogens. To enhance the role of natural salivary defense in controlling oral microbes, oral hygiene products with enzyme and proteins have been developed. The most clinically effective enzymes have amyloglucosidase and glucose oxidase as the active ingrediants. This results in reduction in the accumulation of bacterial plaque and reduces the gingival inflammation [25].

7. Humectants

Humectants are the short chain polyalcohols which prevents the loss of water content in hardening of toothpaste in tube or in when contact with air, it may also gives the creamy texture to the toothpaste. Substances which are used in humuctants are commonly used in food and pharmaceutical industry and should prevents the mineral health risk whem it is used in toothpaste. But sorbitol in higher dosage can cause issues, so the sorbitol intake is being limited to 150mg/kg/day by the FAO/WHO [26].

8. Essential oils

Essential oils like menthol and eucalyptol have the antibacterial activity by changing the bacterial cell wall, by significantly reducing the bacterial plaque and gingivitis. It is mainly used as the antibacterial agents. For reducing the risk of oral condition, herbal tooth paste with natural antibacterial agents could be used in both the children and adults. The essential oils from thyme, clove, propolis have the wide property of antibacterial, antiviral, antioxidant, anti inflammatory and antifungal effects, which prevents the growth of gram-positive and gram-negative bacteria [27].

9. Solvents

The most commonly used solvent is water. It dissolves with the other ingrediants and allows them to mix. Ethanol is used in mouth washes and as both the solvent and taste enhancer [28].

10. Carragenam

Carragenam in toothpaste serves as a naturally derived binding ingredient used in toothpaste. It is a natural material obtained from an edible species of red seaweed. It is a great alternative ingredient that replaces synthetic thickeners [29].

11. Gelling agents / Binders

Gelling agents helps in stabilizing the toothpaste and prevents in separation of liquid and solid phases. They are hydrophilic colloids that disperse or increase the volume in the presence of water [30]. Most used binding agents are:

a. **Sodium Carboxy methylcellulose (CMC):** This compound is physiologically inactive and dissolves in water. It is very compatible with other ingredients [31].
b. **Sodium alginate:** It consists mainly of sodium salt of alginic acid which is odorless and tasteless powder. It is soluble in water forming a viscous solution and its insoluble in ether or ethanol. It also acts as thickeners in preparation of water-miscible pastes, creams and gels [32].
c. **Xanthan gum:** It was a water-soluble powder (hot or cold) which forms viscous that remains unchanged by changing in pH or temperature. With most of salts, moderate surfactant concentrations and most of preservatives it is more compatible. It may tolerate the alcohol concentrations of up to 50% [33].

12. Flavoring agents

Flavoring agent main role is to suppress the unpleasant taste of other component which is used in formulation of toothpaste. With the help of surfactants, the flavoring agent is dispersed in paste or liquids. Water insoluble essential oils like pepper mint, eucalyptus or mint or essential oils like anise, cloves, cumin, thyme, or cinnamon was used as the flavoring agents. As like the flavoring agent's sweeteners could also improve the taste of toothpaste. The most commonly used sweeteners may involve sodium saccharin, sorbitol and glycerin are used [34].

13. Coloring agents

For attractiveness over the toothpaste the coloring agents could be used. The Color Index (CI) has classified the coloring substances, which is published by the society of dyers, colorist and the American Association of Textile Chemists and Colorists, or by a system called FD & C Colors. Titanium Dioxide gives the white color for the toothpaste [35].

14. Preservatives

Preservatives are mainly used in preventing microbial growth in toothpaste. Benzyl alcohol could act as both preservative and flavor enhancer. The most commonly used preservatives are sodium benzoate and methyl paraben which is used in toothpaste. Triclosan was also a preservative which is used in antibacterial and anti-fungal properties which is also used in soaps, hand washes, deodorants, and antibacterial hand gels [36].

Conclusion:

The extraction of fluoride from tea leaves and its formulation into the toothpaste, high lighting the potential of natural sources for enhancing dental health products. The extraction process yields a fluoride concentration that is effective for caries prevention, show casing the viability of using tea leaves as a sustainable source of fluoride. By using the fluoride as a natural extract, it could be eco-friendly product and it would not cause any health issues. Upcoming researches should focus mainly on long term clinical evaluations to access the efficiency of the formulated toothpaste. Overall, this work contributes to the advancement of natural dental care solutions, promoting both oral health and environmental sustainability.

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