ENVIRONMENTAL SCIENCE FOR SUSTAINABILITY

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Editors:
Dr. Yashodhara Varale
Dr. Gangotri Nirbhavane
Dr. Amol S. Shyamkuwar
Dr. Nandita Jena

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Editors

Dr. Yashodhara Varale

Dr. Ambedkar College of
Commerce and Economics,
Wadala, Mumbai

Dr. Gangotri Nirbhavane

Department of Environmental Studies,
Dr. Ambedkar College of Commerce &
Economics, Wadala, Mumbai

Dr. Amol S. Shyamkuwar

Department of Microbiology,
S. S. Jaiswal College,
Arjuni/Mor, District – Gondia, M.S.

Dr. Nandita Jena

Department of Crop Physiology,
Faculty of Agricultural Sciences,
SOA DU, Bhubaneswar, Odisha

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PREFACE

Environmental sustainability has emerged as one of the foremost challenges and responsibilities of our time. With escalating demands on natural resources and the increasing impact of human activities on ecosystems, a profound understanding of environmental science is essential for fostering practices that protect and sustain our planet. Environmental Science for Sustainability aims to provide readers with a comprehensive understanding of the principles and practices that support a sustainable future, blending theoretical knowledge with real-world applications.

This book is structured to cover a wide range of topics essential for environmental sustainability. From ecosystem dynamics, pollution control, and waste management to renewable energy, conservation practices, and sustainable urban development, each chapter offers a detailed exploration of how science can guide us toward more sustainable choices. Beyond presenting key scientific concepts, we aim to inspire critical thinking about the complex relationships between human activities and the natural world, equipping readers to approach environmental issues with both rigor and creativity.

As environmental concerns transcend national borders, so must our solutions be globally informed and locally relevant. The authors have therefore drawn upon diverse case studies and contemporary research to illustrate how sustainability efforts vary across different regions and how we can adapt solutions to address unique environmental contexts.

This book is designed not only for students and professionals in environmental science but also for anyone committed to understanding and addressing the environmental challenges of the 21st century. We hope that it will serve as a valuable resource for fostering the knowledge, skills, and motivation needed to build a sustainable future for all.

- Editors

TABLE OF CONTENT

OPTIMIZING MUNICIPAL SOLID WASTE MANAGEMENT IN ORAN: INSIGHTS FROM THE 3R-VE MODEL

Islam Safia Abdelli*, Dahmane Sanaa,
Fatiha Abdelmalek, Meriem Toumi and Ahmed Addou
Laboratory of Science and Technical Environment and Valorization,
Faculty of Science and Technology. Department of Process Engineering. University Abdelhamid Ibn Badis, Mostaganem, 27000. Algeria.
*Corresponding author E-mail: safia.abdelli@univ-mosta.dz

Abstract:

This study explores the evolution and optimization of waste management practices in Oran through the 3R-VE (Reduction, Reuse, Recycling - Valorization and Elimination) approach. Analyzing municipal solid waste data from 1980 to 2022, it highlights shifts in waste generation and composition and the transition to modern disposal methods, including sanitary landfills. Despite legislative efforts like Law 01-19 and the National Waste Agency's initiatives, waste treatment efficiency remains a challenge. In 2022, less than 1% of the 693.5 million tons of waste was composted, and about 11% was recycled, leaving 88% unprocessed. The study emphasizes missed opportunities from insufficient recycling, noting that energetic valorization of organic matter could yield 123.5 MWh/day, and composting could generate over 5 million US dollars annually.

The study advocates for policy enhancements, such as mandatory sorting and selective collection, to support Oran's transition to a circular economy. Effective sorting is important for the proposed waste solutions, which could create 40,000 direct jobs and over 200,000 indirect ones. By adopting the 3R-VE principles, the study envisions a sustainable and resilient waste management system in Oran, aligning with national sustainability goals and improving the quality of life in Oran and Algeria.

Keywords: Municipal Solid Waste, Recovery, Recycling, Valorization, circular economy, Oran, Algeria.

Introduction:

The management of municipal solid waste (MSW) represents a significant challenge for countries worldwide, encompassing environmental, socio-economic, and public health aspects (Hassaine and Abrika, 2023). Algeria, like several other developing countries, faces considerable hurdles in this domain, with negative implications for public health, the economy, and the environment. In 2020, Algeria generated approximately 34 million tons of waste, including 13 million tons of MSW. The daily per capita waste production has increased from 0.5 kg during

1987-1998 to 0.80 kg in 2020, surpassing the national GDP growth rate and reflecting substantial consumption patterns (NAW, 2020; Mate, 2008).

One primary limitation in Algeria's current waste management system is the low recycling rate, which remains below 10% despite 60% of the waste being recyclable. This rate is notably lower than those of developed countries, such as Germany and Singapore, which reached 67% and 60.5% respectively in 2019 (Sharma *et al.*, 2028, OECD, 2020). Without effective prevention policies, Algeria's waste production could exceed 76 million tons by 2035, highlighting the urgent need for advanced waste management methods (Hassaine and Abrika, 2023).

To address these challenges, Algeria's national waste management policy initially focused on creating controlled dumpsites and establishing landfills to replace illegal open dumpsites. However, the adoption of a linear waste management model has led to significant delays, with landfills rapidly reaching saturation. Approximately 80% of MSW produced in the country ends up in landfills, while the recycling rate remains below 10%, leading to considerable economic losses estimated at around 296 million US dollars annually due to the lack of waste valorization (Hassaine and Abrika, 2023; NAW, 2020).

Shifting to a circular economy (CE) model is important for sustainable development, emphasizing the reduction, recycling, and reuse of resources. The CE aims to minimize natural resource waste, reduce environmental impacts, and enhance resource use efficiency throughout a product's lifecycle. The National Strategy for Integrated Waste Management and Valorization, initiated for 2035, aims to cut municipal solid waste by 6 million tons, achieve a 25% recycling rate, and a 50% composting rate, generating an estimated valorization value of 651 million US dollars and creating numerous jobs (Dahmane *et al.*, 20224). This strategy aligns with global sustainable development goals and represents a shift towards more responsible and sustainable waste management practices.

Environmental damage is a critical concern, threatening present and future generations. The Brundtland Report (1987) emphasized sustainable development (SD), recognizing environmental problems driven by a linear economic model focused on consumer demand. The circular economy (CE), advocating the 3 Rs (reduce, recycle, reuse), aims to extend the life of existing resources, reintegrating them into the economic circuit and minimizing raw material extraction.

Effective waste management from the CE perspective ensures that resources are reintegrated into the economic circuit, enhancing the performance of the economic system and reducing environmental degradation. Several organizations, including the United Nations (UN) and the European Union (EU), have adopted large-scale energy and environmental policies to facilitate this transition. The EU's Directive 2008/98/CE and subsequent measures highlight the importance of optimal resource management and the promotion of the CE (Collard, 2020).

In Algeria, despite efforts to integrate CE principles, the recycling rate remains below 7%. The country's reliance on hydrocarbons and imported products, coupled with a lack of a diversified economy, impedes the effective reintegration of products into the economic circuit. The unrealized recycling potential represents a significant economic loss, underscoring the need for a comprehensive recycling policy and efficient waste management (Dahmane *et al.,* 20224).

This book chapter aims to analyze the inadequacies of previous waste management programs and evaluate the relevance of the National Strategy for Integrated Waste Management for 2035 (NSIWM-2035) in introducing new instruments for sustainable and integrated waste management. By absorbing CE principles, this strategy has the potential to unleash economic opportunities and improve waste management in Algeria, moving beyond reactive and linear approaches.

In summary, this chapter seeks to contribute to the ongoing discourse on waste management in Algeria by providing a comprehensive analysis of current practices and proposing a pathway towards a more sustainable and economically viable future through the implementation of circular economy principles.

Study Area Description

Figure 1: Location of Oran city

As illustrated in Figure 1, Oran is strategically located in northwest Algeria and is distinguished as the country's second-largest city. It is undergoing a period of remarkable demographic and economic expansion. As of 2022, the city's population has reached 2,296,026 inhabitants, accompanied by key economic indicators such as a Gross Domestic Product (GDP) per capita of $5,130, a projected real growth rate of 3.1% for 2024, an unemployment rate of 11%, and an average monthly income of approximately 420 USD (Dahmane *et al.,* 20224). This swift growth trajectory has resulted in a significant uptick in daily waste production, which currently surpasses 1,900 tons. As a pivotal hub for regional and national development, Oran is confronted with challenges in urban planning, infrastructure, and waste management. It is imperative for the city to adopt efficient and sustainable waste management practices to accommodate the escalating demand and to ensure the well-being of its growing population.

While cities such as Singapore and Stockholm have successfully addressed similar challenges through innovative waste management strategies and robust environmental policies (NEA, 2021), Oran also has significant potential, particularly in resource valorization from waste. Learning from successful approaches in other developing regions, like Curitiba in Brazil, Oran can leverage strategic planning and government initiatives to advance towards more sustainable waste management practices. This shift would not only enhance environmental protection but also support the region's overall development (Rahmasary *et al.,* 2019)

Current Status of Municipal Solid Waste Management in the City of Oran

The city of Oran has experienced significant changes in its approach to municipal solid waste management over the past decade. Until 2012, the primary method of handling waste was through collection, transportation, and open dumping. This method, while common in many developing regions, resulted in substantial environmental and public health issues. Recognizing these challenges, the city initiated a series of reforms beginning in 2016.

One of the most notable changes was the elimination of all open dumpsites, including the closure of the El Kerma dumpsite, previously the second-largest dumpsite in Algeria. In place of these open dumps, Oran adopted a hybrid model of waste management, which included the construction and operation of sanitary landfills. This new approach featured three Class II landfills, reclaiming a total area of 205 hectares that had been previously used for open dumping (Abdelli *et al.,* 2020). This transition towards more regulated waste management practices represents a significant step towards achieving responsible and environmentally sustainable waste management in Oran.

As of now, the city boasts a collection coverage rate of 84%. Despite these improvements, the region continues to face challenges related to waste management and valorization. In 2020, Algeria produced a total of 13.5 million tons of MSW 90% being MSW and the remaining 10% consisting of assimilated waste from economic and administrative activities, including industry, commerce, services, and administrations (Abdelli *et al.,* 2020).

The NSIWM -35 outlines different scenarios to manage the increase in waste production. Under the Business As Usual (BAU) scenario, the quantity of MSW is projected to reach 23 million tons by 2035. However, if the strategy is effectively implemented, incorporating measures such as prevention and financial incentives, the quantity could be limited to 20.5 million tons, with a recycling rate potentially reaching 25% to 30% (Dahmane *et al.,* 20224).

Despite Oran's economic significance, research on municipal solid waste management remains relatively limited. Existing studies primarily focus on quantifying MSW production, with less emphasis on comprehensive waste management and valorization strategies. This highlights the need for more in-depth research and data collection to inform better waste management practices.

Significant contributions to the research on MSW management in Oran have been made by Tabet Aoul *et al.* (2000), Benaama *et al.* (2011), and Bentekhici (2019). These studies, however, may not fully cover all dimensions of management. More in-depth investigations by Dahmane (2012), Bouhadiba *et al.* (2015), Abdelli *et al.* (2017), and Abdelli *et al.* (2020) provide detailed analyses of specific aspects of MSW management. Despite their focused approach, these studies may still leave gaps in understanding the broader context and complexities of municipal solid waste management. Therefore, while each study offers valuable insights, further research synthesizing and expanding upon these findings is necessary to build a comprehensive knowledge base on MSW management in Oran.

Drawing from successful sustainable waste management practices in other developing and developed countries, such as Brazil, India, and Sweden, can provide valuable insights to improve Oran's waste management (Coelho *et al.*, 2021; Rana, 2018). The transition towards a mixed model of municipal solid waste management, including the establishment of sanitary landfills, represents a positive move towards more controlled and environmentally respectful waste management practices. By adopting best international practices, Oran can enhance its waste management capabilities and progress towards a more sustainable and prosperous future.

Integrated Analysis of MSW Evolution

1. Study of the Evolution of MSW generation from 1980 to 2022

The city of Oran has witnessed a significant evolution in the quantities of MSW generated over the past decades. Prior to 2013, the amount of waste produced increased dramatically, rising from 574.4 tons per day in 1980 to 1,201.6 tons per day in 1998, and reaching 1,523 tons per day in 2003 (Dahmane, 2012). This escalation in waste production per inhabitant is illustrated in Figure 2, where the daily waste generation per capita increased from 0.76 kg in 1980 to 0.99 kg in 1998, and further to 1.05 kg in 2003. These figures are significantly higher than the national averages, which were 0.35 kg /inhab/ day in 1980 and 0.65 kg/inhab/day in 2000 (NAW, 2020). However, they are comparable to the quantities generated in France, which were 0.79 /inhab/day in 1980, 0.97 kg/inhab/day in 1998, and 1.07 kg/inhab/day in 2009 (ADEME, 2009).

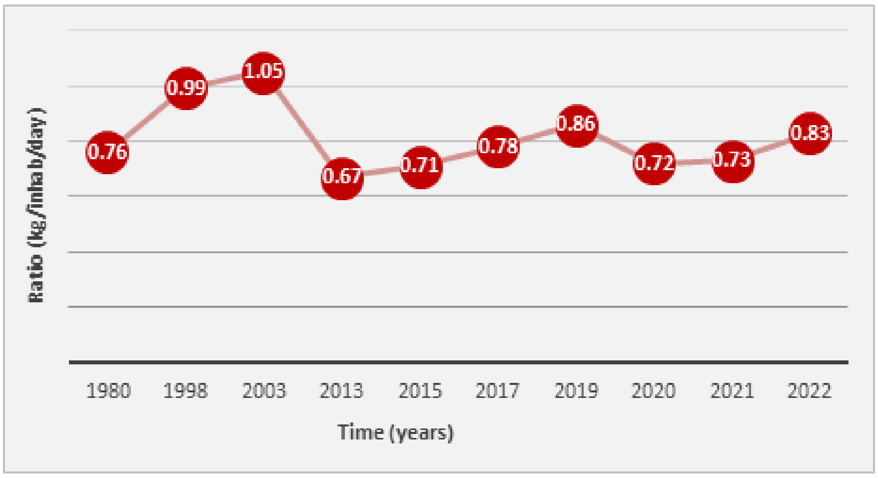

Figure 2: Quantitative evolution of MSW from 1980 to 2022

The high ratios of MSW production in Oran reflect a situation that does not accurately represent the actual waste management practices, especially after the opening of sanitary landfills. These overestimated figures are explained by the approximate calculation methods used, including the volume of trucks entering the landfill and the number of daily rotations. Following the introduction of sanitary landfills in 2012, the quantities of waste showed a notable decrease, dropping from 1,523 tons per day in 2003 to 1,062 tons per day in 2013. Consequently, the per inhabitant waste generation ratio fell from 1.05 kg to 0.67 kg per day, marking a 36% reduction. This decrease is attributed to the implementation of more accurate weighing of the waste redirected from open dumping to landfills.

Between 2013 and 2019, the quantities of MSW remained relatively stable, with an annual growth rate of 9%. The respective daily waste quantities for these years were 1,062.8 tons in 2013, 1,167.12 tons in 2015, 1,328.8 tons in 2017, and 1,518.3 tons in 2019. The per capita waste generation also increased, from 0.67 kg per day in 2013 to 0.71 kg in 2015, 0.78 kg in 2017, and 0.86 kg in 2019. This increase in waste quantities is linked to economic development, urbanization, and improvements in living standards, which led to a 6% annual increase in goods consumption and the complexity of the generated waste.

However, the COVID-19 pandemic in 2020 had a significant impact on waste quantities due to decreased purchasing power and the shutdown of many economic, industrial, and commercial activities. Consequently, the quantities of waste treated at the CET decreased by 19.5%, from 1,518.3 tons per day in 2019 to 1,294 tons per day in 2020. In 2021, a slight increase of 3.11% was observed, with quantities reaching 1,385.6 tons per day. The per capita waste generation ratio also fluctuated, dropping from 0.86 kg per day in 2019 to 0.72 kg in 2020, and then slightly rising to 0.73 kg in 2021 as activities resumed post-confinement. These variations are consistent with the national averages reported by the National Waste Agency, which were 0.8 kg per inhabitant per day in 2019, 0.67 kg in 2020, and 0.68 kg in 2021 (NAW, 2020).

In 2022, waste production increased by 12% compared to the previous year, reaching 1,545.85 tons per day, with the per capita production ratio returning to 0.83 kg per day. Despite this increase, the quantities remain below the pre-COVID-19 levels. Additionally, the National Waste Agency reported that Oran is the largest producer of MSW in Algeria, followed by the capital, Algiers, with a production ratio of 0.77 kg per inhabitant per day, while the national average is 0.68 kg per day (NAW, 2020).

The evolution of MSW quantities in Oran underscores the importance of implementing integrated waste management policies that can adapt to economic fluctuations and exceptional events like health crises. Continuous improvement of waste management infrastructure and practices is essential to ensure sustainable and responsible MSW management in Oran, while minimizing the associated environmental and social impacts.

By adopting innovative and efficient waste management techniques, such as recycling, composting, and waste-to-energy technologies, the city can optimize resource utilization and reduce the amount of waste sent to landfills. Public awareness and education campaigns can also encourage responsible waste disposal practices, promoting waste reduction and proper sorting. An integrated approach to waste management can create economic opportunities, such as job creation in the recycling sector and the development of a circular economy, where waste materials are used as resources for new products and processes.

Local authorities should establish contingency plans to handle unexpected events, like pandemics, ensuring that waste management services continue to function efficiently during challenging times. Overall, a proactive and adaptive waste management strategy, supported by collaboration between stakeholders, policymakers, and the public, can contribute to a cleaner and more sustainable environment for Oran, while enhancing the well-being of its residents and preserving valuable resources for future generations.

2. Study of MSW Composition in Oran

Understanding the quantity and composition of MSW is important for devising appropriate treatment methods and developing sustainable waste management strategies. In Algeria, the predominant methods of waste disposal are landfilling and dumping, which account for 97% of waste management practices (Djemaci *et al.*, 2018, Abdelli *et al.*, 2017). A precise knowledge of MSW composition allows for targeted actions such as recycling, composting, and energy recovery, which in turn reduce landfill waste and mitigate environmental impacts such as pollution and greenhouse gas emissions. Table 1 summarizes the evolution of MSW composition generated by the city of Oran from 1984 to 2021.

Table 1: Evolution of MSW Composition in Oran (Percentages by Weight)

Materials	1984	1992	2003	2010	2015	2019	2022	National Average
Organic Matter	72	69	72.5	54.4	52.5	52.7	51.5	53.6
Paper/Cardboard	16	16	9	6.6	12.7	6.6	6.4	6.7
Textiles	2.6	-	2	3.3	2.8	2.36	3.4	4.5
Sanitary Textiles	-	-	-	6.3	10.4	7.8	14.6	11.8
Plastics	2.5	2.5	12	24.9	12.3	12.8	17	15.3
Metals	2.4	2.5	1.7	1.7	1.7	2.6	1.1	1.7
Glass	1.2	-	1.8	1.2	1.1	1.4	0.6	1.0
Others	3.2	10	0.6	1.2	4.2	9.86	2.70	2.72
References	Tabet – Aoul, 2000		Dahmane, 2012		Dahmane *et al.*, 2024	NAW, 2020	Dahmane *et al.*, 2024	NAW, 2020

The composition of MSW in Oran has undergone significant changes over the past decades. Before 2010, organic waste constituted over 70% of the total waste composition. This trend is consistent with other cities in Algeria, such as Msila, Blida, Constantine, Chlef, and Algiers (Derias *et al.,* 2022). However, over time, the waste composition has become more complex with the emergence of materials like plastics, sanitary textiles, papers, and diapers. This shift is attributed to changes in lifestyle, dietary habits, and an increase in purchasing power.

From 1984 to 2021, several notable trends were observed in the MSW composition in Oran:

1. **Decrease in Organic Fraction**: The organic fraction of MSW decreased by 20% between 1984 and 2015, though it remained above 50% in 2019 and 2021. This decline is linked to increased consumption of processed and packaged products.
2. **Change in Packaging Type**: There was a significant shift in packaging types from paper/carton to plastic. In 1984 and 1992, paper/carton accounted for 16% of waste compared to 2.5% for plastic. By 2015, plastic waste had increased to 16.98%, while paper waste had decreased to 6.45%.
3. **Impact of COVID-19**: The pandemic caused a notable reduction in waste quantities due to lockdown measures and decreased purchasing power. The plastic fraction decreased to 12.3% in 2020, while the paper fraction increased to 12.7%.
4. **Stability of Metal Fraction**: The metal fraction remained relatively stable, fluctuating between 2.4% and 2.5% from 1983 to 1992, with a slight increase to 2.56% in 2019 before declining to 1% in 2021.
5. **Emergence of New Fractions**: New waste fractions, such as sanitary textiles emerged since 2010 due to population growth and increased commercial activities.

These changes in waste composition reflect shifts in consumption patterns, lifestyle, and economic activities in Oran. Addressing these new waste streams requires tailored waste management strategies, including selective collection, recycling, energy recovery, and public awareness campaigns.

3. Regression Analysis of Oran's MSW

A regression analysis was conducted on the MSW generation in Oran, revealing a clear upward trend in waste production over the analyzed period. Using historical data from 1980 to 2022, a linear regression model established the relationship between years and MSW generation in tons per day. The analysis indicated an average increase of 23.17 tons/day per year, with an R-squared value of 0.86, demonstrating a strong correlation between temporal progression and waste generation.

Furthermore, polynomial regression analysis was employed for individual waste components (organic matter, plastic, textile, metal, and glass) to derive equations representing the change in percentage of each component over time. The resulting equations are as follows:

1. **Organic Matter**: Percentage$=-0.2665x^2+110.52x-110243.69$
2. **Plastic**: Percentage$=-0.0045x^3+17.295x^2-20836x+8075140$
3. **Textile**: Percentage$=-0.0029x^2+11.676x-11580.072$
4. **Metal**: Percentage$=-0.0008x^3+3.0686x^2-3820.3x+1516114.4$
5. **Glass**: Percentage$=0.0007x^3-5.1135x^2+12226x-9633886$

These equations provide mathematical insights into how the composition of MSW has evolved over the years. Analyzing the coefficients and terms in these equations reveals trends and patterns of change in each component's percentage within MSW. This understanding is essential for developing effective waste management strategies aimed at promoting sustainability and efficient resource utilization.

The evolution of MSW generation and composition in Oran highlights the need for adaptive and sustainable waste management practices. Investing in waste reduction initiatives, upgrading infrastructure, and enforcing regulations are crucial steps. Embracing innovative techniques such as recycling and waste-to-energy technologies can reduce landfill waste while promoting economic growth. Public awareness campaigns and contingency plans for unforeseen events are also essential components. Collaboration among stakeholders is vital for implementing these strategies, ensuring a cleaner and more sustainable environment for Oran.

Application of the 3R-VE Principle

The 3R-VE principle (Reduce, Reuse, Recycle - Valorize, and Circular Economy) is pivotal for waste management in Oran. It aims to minimize waste and maximize its reuse and valorization, thereby promoting a circular economy. This principle is applied locally through policies and strategies aligned with sustainable development. Legislation governs waste management, control, and disposal, accompanied by action plans for the integrated management of special waste and municipal solid waste.

By 2035, Oran aims to reduce municipal solid waste by 10%, achieve a valorization rate of 47%, and eliminate 1,300 illegal dumpsites. However, in 2018, only 1% of waste was composted, about 10% recycled, and 82% disposed of in landfills. The strategy to achieve these goals includes promoting reduction at the source, reuse of products, and energy recovery from residual waste (Dahmane *et al.*, 2024)

1. Prevention

Prevention is the key element in waste management, aiming to reduce waste accumulation by promoting recycling and material valorization. This approach treats materials as resources rather than waste, fostering a circular economy. The adoption of prevention strategies benefits the environment and creates green jobs, especially in the circular economy sector. The transition to a circular economy involves rethinking production and consumption patterns to minimize waste generation.

Promoting the circular economy and green jobs requires collaborative efforts from various stakeholders, including government, businesses, citizens, and civil society. It is important to raise awareness about waste prevention and implement policies favoring source reduction, product reuse, and material valorization. In Oran, prevention is a critical pillar for sustainable waste management, leading to the creation of an innovative environmental industry and contributing to the preservation of natural resources. Collective and concerted action is essential for addressing environmental challenges while fostering sustainable economic development in the region.

2. Recovery

In Oran, waste valorization efforts have been primarily focused on four main categories: plastics, paper/cardboard, ferrous metals, and aluminum. Figure 3 illustrates the evolution of the quantity of these materials recovered between 2015 and 2020.

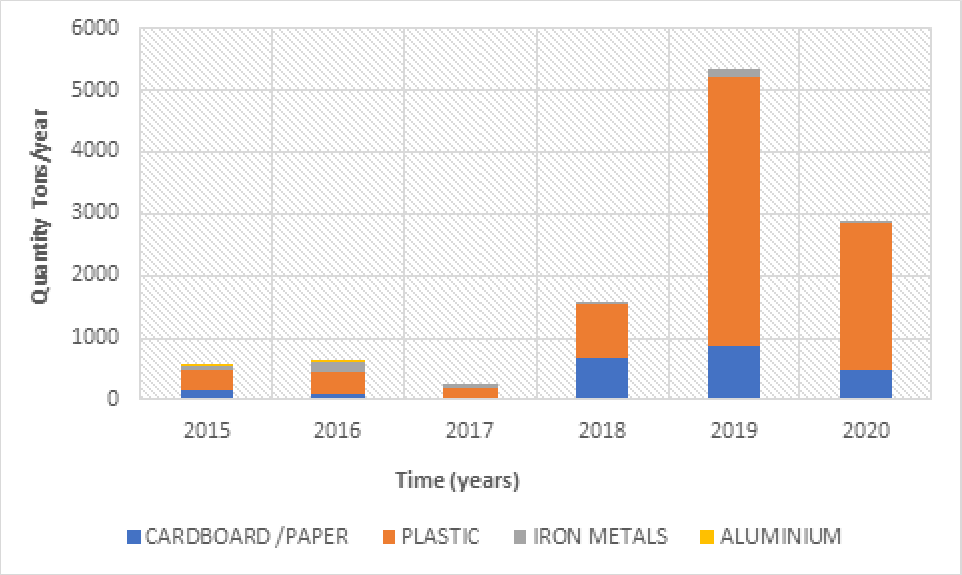

Figure 3: Evolution of municipal solid waste recovery in the city

In Oran, waste valorization efforts have been primarily focused on four main categories: plastics, paper/cardboard, ferrous metals, and aluminum. The selective sorting projects launched in 2015 initially saw low recovery rates for these materials. However, after their discontinuation in 2017, the recovery efforts were limited to the operating bins at the city's landfills. A significant growth in the amount recovered was observed in 2018, driven mainly by the economic value of plastic. This trend continued with plastics constituting the majority of recovered materials, exceeding 5,000 tons per year by 2019. In contrast, the quantities of recovered paper/cardboard and ferrous metals, although slightly higher than in previous years, remained relatively low, with annual volumes well below 1,000 tons.

The COVID-19 pandemic in 2020 led to a slight decrease in overall recovered volumes, particularly affecting plastics. This decline can be attributed to the impact of the pandemic on the recycling market, including a drop in the price of virgin plastic raw materials compared to recycled plastic (Singh *et al.*, 2022). Aluminum represents the category with the lowest quantity recovered, mainly due to the absence of a well-established recovery channel, unlike ferrous metals, plastics, and paper/cardboard.

An analysis conducted in 2019, chosen as the reference year, revealed the following recovery rates and economic potential of the materials:

- Cardboard/Paper: 874.8 kg/day recovered with a recovery rate of 2.73%.
- Plastic: 4,337.32 kg/day recovered with a recovery rate of 7.01%.
- Ferrous Metals: 129.56 kg/day recovered with a recovery rate of 1.04%.

These figures illustrate the current state of waste recovery in Oran and the economic potential that remains untapped. The low recovery rates, despite the high proportion of recyclable waste, indicate the need for improved strategies and infrastructure to enhance waste valorization and move towards a more sustainable and economically efficient waste management system.

Theoretical estimates for 2021 and 2022 suggest that the recovery volumes of plastics could have been 82,701 tons in 2021 and 85,182 tons in 2022, with potential sales of over \$13.6 million and \$14 million, respectively. However, these figures do not reflect the reality on the ground. The actual recovery rate of plastics barely exceeds 7%, leaving the majority of these materials outside the valorization channels. A similar phenomenon is observed for ferrous metals, with theoretical volumes estimated at over 5,500 tons, but an actual recovery rate barely above 1%. As for paper/cardboard, despite projected volumes of over 31,000 tons in 2021 and 32,000 tons in 2022, their recovery rate remains below 3%.

These significant discrepancies between theoretically recoverable quantities and actual recovery rates highlight considerable economic losses for the city of Oran. The non-valorization of these materials represents a missed opportunity to generate substantial revenues, while also contributing to the reduction of the ecological footprint. The valorization channels, particularly for ferrous metals and paper, appear underutilized, leading to avoidable financial losses and waste of valuable resources. It is imperative to rethink current strategies to improve recovery rates, maximize the value of recyclable materials, and fully exploit the economic potential of waste, while reinforcing the transition towards a sustainable circular economy.

Several critical observations underscore this situation:

- The shift from open dumpsites to landfills did not fulfill the primary objective of integrated solid waste management, which is promoting material valorization.
- Municipal solid waste management often focuses on collection, transportation, and landfill disposal, with insufficient emphasis on recycling and material valorization.
- Local authorities have yet to actively develop a value chain for waste recovery and promote material valorization.

- The formal waste sector heavily relies on the informal sector, which dominates the recovery of plastics, non-ferrous metals, paper, and cardboard.

Developing valorization channels on a national scale is essential to alleviate pressure on landfills and foster a more circular and sustainable economy. In the long term, waste recovery could significantly increase sector revenues if compostable and recyclable products are processed to meet international quality standards. Comparing the prices of these recycled products with international prices is crucial to establish efficiency ratios. For instance, the profit margins could be up to 1.5 times for plastic if converted into fuel, 2 times for paper, 3 times for compost, 3.5 times for glass, and 8 times for metals (Hassaine and Abrika, 2023). However, several factors, such as the quality and quantity of compostable and recyclable products, necessitate expertise in valorization and source sorting.

Achieving the goals of the NSIWM-2035 and financially empowering Algeria's waste sector requires a significant increase in the current recovery rate for municipal solid waste, which is currently insufficient to cover transport costs. Increasing this rate to 1% of MSW income is essential (NAW, 2020). Moreover, composting and recycling processes can have negative environmental impacts if transformation standards are not aligned with the Sustainable Development Goals (Hassaine and Abrika, 2023).

A SWOT analysis conducted by Doumani (2017) on the overall waste sector highlighted that the strategic framework of the NSIWM-2035 is in development, with indications of political will for its implementation. The potential for recycling and composting presents an opportunity for Algeria in terms of cost reduction, job creation, and environmental benefits (Doumani, 2017).

However, weaknesses and threats currently outweigh strengths and opportunities. Challenges include developing a specific taxation system for waste and the low recovery rate for both MSW and special waste. The regulatory, institutional, organizational, and incentive frameworks are not sufficiently aligned to support manufacturers in complying with regulations. Consequently, the private sector remains marginalized in waste collection, landfill, and processing. The waste sector is dominated by the informal sector, which is challenging to regulate. Awareness-raising and communication efforts have also been sidelined in the national strategy. Exogenous threats, such as international and regional shocks, could hinder foreign investment in the waste sector. The 51/49 rule established by the Algerian government, which restricts foreign financing and loans, deters international companies and institutions from investing. The authorities responsible for implementing the NSIWM-2035 might see minimal impact due to their marginalization in the strategy's development (Hassaine and Abrika, 2023).

3. Recycling

Recycling presents significant opportunities for Algeria, offering both economic and environmental benefits such as reduced raw material imports, preservation of natural resources, creation of green jobs, and waste reduction. To fully realize these advantages, additional efforts are needed to develop the recycling sectors and promote education. Accredited training structures, including higher education institutions, are increasingly involved in fostering recycling-related skills.

The waste sector in Algeria, particularly in Oran, is identified as a promising area for transitioning to a circular and sustainable economy. By developing recycling chains and emphasizing education and innovation, Algeria can decrease its reliance on raw material imports, create new business opportunities, and generate jobs in the recovery sector. This transition towards recycling can yield economic, environmental, and employment benefits, fostering a more circular, sustainable, and resilient economy while reducing environmental impact.

Addressing the significant challenge of rising plastic consumption in Algeria, with an annual growth rate of 11% over the past ten years, the per capita usage has increased from 10 kg/person in 2007 to 23 kg in 2017, projected to reach 25.8 kg in 2020 (Dahmane *et al.*, 2024). Nearly 60% of the plastic consumption is related to packaging, 20% is used in the building and construction sector, while the rest is utilized in other plastic industries. Plastic waste accounts for a significant portion of the annual municipal waste, approximately 15.31% of the total, resulting in around 2.1 million tons of plastic waste generated annually. However, the plastic recycling rate in Algeria is about 15%, indicating potential for improvement in the management and recycling of plastic waste (Hassaine and Abrika, 2023; Djemaci, 2012).

Regarding paper recycling, the existing capacity of the local paper industry in Algeria does not exceed 10% of the total waste generated annually. The national consumption of paper and cardboard is estimated at 600,000 tons per year, while local production does not exceed 50,000 tons per year. Paper and paper derivatives import amount to nearly 289.5 million US dollars, and approximately 335,000 tons of paper waste are buried annually. However, the local company Tonic Emballage in Algeria plans to increase the recycling rate from 10% to 38% through improved sorting, selective collection, and government support for small recycling businesses (Abdelli *et al.,* 2020; Djemaci, 2018).

This highlights Algeria's potential for recycling improvement, particularly for plastic and paper waste. Investing in sorting infrastructure and encouraging small recycling businesses can reduce import dependence, decrease waste burial, and preserve natural resources. Proactive recycling contributes to environmental protection by limiting pollution. The growth of plastic recycling depends on establishing primary sorting infrastructure for high-quality recycled plastics.

Algeria is currently focusing on waste management with selective collection centers and sorting facilities, promoting the emergence of a national waste recovery and valorization industry. Public and private sectors, supported by organizations like Support National Microcredit Management, National Agency for Youth Employment, and National Investment Development

Agency. Algerian operators have recently launched PET valorization units, demonstrating positive progress in this area. Training programs for waste management professionals are important for proper recycling channel functioning. Algeria aims to increase material recycling, reaching a 40% or higher recycling rate (Doumani, 2017)

Various mechanisms, from subsidies to regulations and training initiatives, support recycling development. Oran city has seen a positive trend in waste recovery activities, with an increase in registered companies. MSW valorization, especially composting for the organic fraction, is emphasized as an effective and sustainable solution. However, any waste management approach must consider socio-cultural and economic impacts on the community, as these factors influence the adoption of waste valorization initiatives.

The first law on waste management of 2001, 01-19, constitutes the reference framework, integrating the universal principles of sustainable waste management, and was the starting point for the development of the National Municipal Solid Waste Management Program (NMSWP). Subsequently, the National Strategy for Integrated Waste Management for 2035 (NSIWM-2035), whose target was to strengthen waste recovery at a recycling rate of 30%, was signed. Tax instruments with an environmental orientation can constitute one of the essential factors in the transition to the circular economy and sustainability (Dahmane *et al.,* 2024; Djemaci, 2012).

In terms of financing, spending on waste management increased from 0.06% of GDP in 2002 (56.76 billion US dollars) to 0.03% in 2016 (159 billion US dollars). However, it is important to point out that these figures are below the minimum expenditures required to reduce the cost of environmental degradation due to waste, which has been increasing constantly, at 0.2% of GDP in 1999, reaching 0.7% in 2011 (Hassaine and Abrika, 2023).

From an operational point of view, burial is the first method of waste treatment in Algeria; from 2002 to 2016, 172 waste treatment facilities, divided between technical landfill sites and controlled landfills, were put into operation (Tolba *et al.,* 2020). Despite these efforts, Algeria, with its considerable economic, environmental, and social potential, is still struggling to truly implement a recycling policy or manage the waste efficiently. The unrealized recycling potential represents 0.25% (USD 412 million) of GDP in 2015 (NAW, 2020), while the amount of household waste recycled is less than 7% (Doumani, 2017).

The public character shows predominance in the waste management sector with 95% state financing (NAW, 2020). The country, which exports 97% of its hydrocarbons and imports almost all the products it uses, lacks a diversified economy and a consistent production structure that would allow products to be reused and reintegrated into the economic circuit.

4. Composting

In Oran, the valorization of organic matter through composting has been a pivotal initiative since 2018, particularly at the wholesale market. The city's cleaning services actively collect green waste, as well as vegetable and fruit scraps from the market, to produce compost. This effort aims to reduce the amount of waste sent to landfills while providing valuable compost for agricultural soils and green spaces throughout Oran.

Despite these initiatives, the actual quantity of compost produced remains relatively modest compared to the total waste generated. Daily, approximately 10 tons of organic waste are produced at the wholesale market, with green waste reception at the landfill ranging from 60 to 80 tons per day during the peak season from September to February. The data of figure 4 indicating the quantity of compost produced, the actual quantity collected, and the loss rates from 2018 to 2022 reveals significant progress: the amount of compost produced increased from 0.3 tons per day in 2018 to 25 tons per day in 2022, while the actual quantity of compost collected rose from 38 to 63 tons per day.

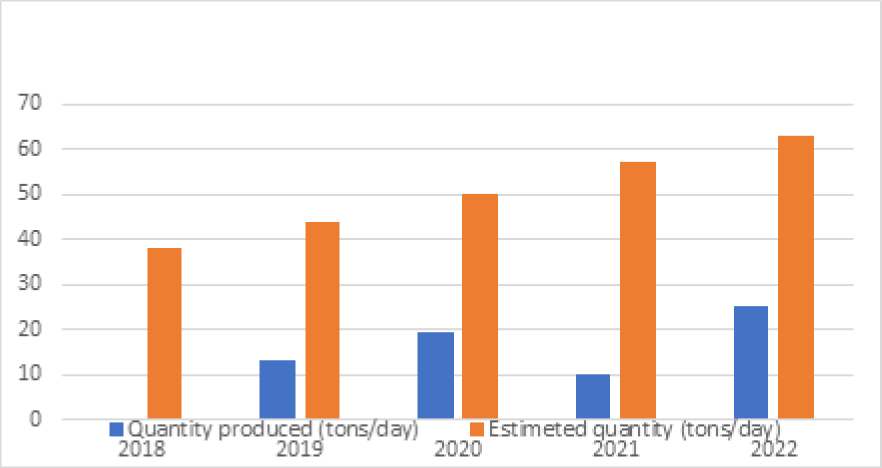

Figure 4: compost produced from the waste of the city of Oran

Moreover, loss rates have generally declined, falling from 0.99% in 2018 to 0.60% in 2022, although some fluctuations have occurred. This reduction in loss rates signifies an improvement in the efficiency of composting systems. However, the valorization of organic waste remains insufficient ; the quantity of organic matter collected from the wholesale market constitutes only 18% of the total organic matter disposed of in landfills, leading to an estimated economic loss of 90% due to non-valorization.

Consequently, it is imperative to continue optimizing the processes of collection and composting to reduce reliance on landfills and enhance the environmental and economic benefits associated with waste valorization.

Investing in composting has significant economic and environmental benefits. Over the past two years (2021 and 2022), potential gains from compost production were estimated at 157,838 tons and 162,573 tons, respectively. The sales revenue from this compost would amount to 5.3 million USD and 5.4 million USD, with potential profits of 3.7 million USD and 3.9 million USD. These figures demonstrate that investing in composting is profitable and environmentally beneficial, reducing landfill waste and producing high-quality organic fertilizers.

To ensure high-quality compost, a source-separated selective collection system is essential. This system requires rigorous collection, monitoring, and control, as well as awareness-raising programs and mechanisms for taxation and/or fines to encourage good practices. By maximizing the potential of composting, Oran can reduce landfilling, conserve resources, and create an environmentally friendly and economically efficient waste management system.

In Algeria, composting remains an underutilized method for waste management. The current model relies heavily on the importation of minerals in the form of N-P-K fertilizers or animal feed to produce fruits and vegetables, which are consumed locally or exported. Waste from these value chains ends up in landfills, and only a portion of animal manure is recycled for vegetable production. The biowaste from agriculture is not adequately recycled, resulting in a continued dependency on imported minerals.

The composting process stabilizes organic waste to produce nutrient-rich compost, containing essential macronutrients like N-P-K-Ca-Mg. This compost can effectively replace imported chemical fertilizers, reducing import dependence and promoting sustainable agricultural practices.

5. Energy Recovery

Energy recovery from municipal solid waste presents a critical solution for addressing the escalating energy demand in both developed and developing nations. Poor waste management not only poses environmental and health risks but also leads to energy losses. However, with a well-crafted waste management policy, it's possible to tackle waste issues while simultaneously addressing the energy crisis. Energy recovery involves converting waste into electricity, heat, or fuel, thereby reducing landfill waste and creating a renewable energy source. This approach not only aids in environmental preservation by curbing greenhouse gas emissions but also promotes the use of clean energy. The implementation of effective policies and infrastructure for waste-to-energy conversion is essential for sustainable waste management, supporting the transition to a low-carbon economy. It is imperative to ensure that energy recovery technologies are environmentally friendly, with stringent emission controls to minimize potential impacts on air and water quality. A comprehensive waste management strategy, encompassing recycling, energy recovery, and sustainable practices, is vital for establishing an efficient and sustainable waste management system, contributing to a cleaner and more prosperous future.

Methanization, with recovery rates ranging from 73% to 80%, offers an immediate solution to the current scenario marked by inadequate collection control, high production of municipal solid waste, and low recovery rates. This valorization technique helps to conserve landfill space by effectively treating the majority of waste types found in municipal solid waste. According to Abdelli *et al.,* 2017, the city of Oran has a significant potential for landfill gas, primarily generated by the anaerobic digestion of biodegradable waste fractions buried in landfills. This landfill gas is mainly composed of CH_4 (35-65 vol. %) and CO_2 (15-40 vol. %) (Chandra *et al.,* 2023).

Consequently, energy recovery through the methanization of municipal solid waste represents an opportunity to meet the increasing energy demand while mitigating the negative environmental impacts associated with improper waste management. It is important to implement appropriate policies and technologies to harness this resource sustainably and cost-effectively. According to Abdelli and al. 2020, the energy potential lost due to the non-valorization of organic matter buried in open dumps and landfills is estimated at 2613.20 GWh. With an average daily production of 193.5 MWh/day, these findings are consistent with those published by Abdelli *et al.* in 2020, indicating that the city of Oran could produce approximately 200 GWh per year, representing 15% of the total electricity demand. This estimate suggests that methane can serve as an economical energy source and significantly reduce greenhouse gas emissions. This information can assist policymakers in assessing the potential for electricity generation from municipal solid waste and the necessary equipment to be installed.

The experimental results from the city of Oran, as described by Abdelli and al. in 2024, reveal a substantial production of methane from the biodegradation of organic waste, with an estimated CH4 production of 19.88 gigagrams annually, equivalent to 27.7×10^6 m^3. This considerable methane emission underscores the environmental impact of unmanaged waste and highlights the urgency for effective waste management strategies. This suggests that a substantial amount of methane is generated from the decomposition of organic matter in waste, emphasizing the need for measures to capture and utilize this potent greenhouse gas (Abdelli *et al.*, 2024).

It is essential to consider these quantities of CH_4 generated by municipal solid waste, as methane is a potent greenhouse gas, and its emissions must be controlled and managed responsibly to reduce the impact of climate change. The energy recovery of methane can be a solution to harness this resource while contributing to the reduction of greenhouse gas emissions.

Conclusion:

This comprehensive analysis of the qualitative and quantitative changes in municipal solid waste in Oran has underscored the critical issues surrounding waste management and pinpointed pathways to foster a more sustainable circular economy. The aim was to evaluate the qualitative and quantitative changes in municipal solid waste and investigate the feasibility of applying the 3R-VE principles (Reduction, Reuse, Recycling - Valorization, and Elimination). Data collected from Oran between 1980 and 2022 showed a substantial rise in the generation of municipal solid waste, peaking prior to 2013.

Notably, the introduction of sanitary landfill sites in 2012 has led to a reduction in the volume of waste, reflecting improved waste management strategies. The makeup of municipal solid waste has transformed over the years, moving from an organic waste majority before 2010 to a mix including plastics, textiles, and paper, reflecting lifestyle shifts and greater purchasing power. The analysis underscored the financial advantages of composting and advocated for increased investment in composting facilities to diminish waste. Moreover, methanization has been recognized as an effective strategy to tackle waste management issues while also aiding in the city's energy requirements. To effectively shift from a linear to a circular economic framework, regulatory measures such as compulsory sorting and the adoption of selective collection are imperative to bolster waste reduction, recycling, and energy recovery efforts. A holistic and coordinated waste management approach is vital for establishing a more sustainable and efficient waste management system in Oran and across Algeria. By embracing the 3R-VE principles and investing in eco-friendly practices, the city can cultivate a vibrant circular economy, lessen its environmental footprint, and enhance its ability to withstand future challenges.

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THE CARBON FOOTPRINT OF TEA: FROM PRODUCTION TO CONSUMPTION

Bidisha Hazarika*[1], B. K. Medhi[2] and A. S. Gogoi[1]

[1]Department of Tea Husbandry & Technology,
Assam Agricultural University, Jorhat

[2]Department of Soil Science, Assam Agricultural University, Jorhat

*Corresponding author E-mail: bidisha.hazarika.adj22@aau.ac.in

Abstract:

The concentration of CO_2 has significantly increased from an annual average of 280 ppm in the late 1700s to 424 ppm in May 2023. The agricultural sector contributes 15-20% of annual global GHG emissions, with tea being a notable agricultural product worldwide. Tea production contributes to greenhouse gas emissions at various stages, from cultivation to consumption, due to its high energy consumption and complex life cycle system. The production stage accounts for 57% of the environmental burden. Different farming management and processing techniques significantly impact the carbon footprint and primary energy demand of tea products. Despite its environmental impact, tea plants exhibit substantial carbon sequestration potential, with mature tea bushes assimilating around 5134.4 ± 831.6 kg CO_2/ha per year in their biomass. Continuous organic cultivation of tea plantations results in a 43% higher above-ground biomass production compared to conventional systems, with notable below-ground carbon accumulation. However, tea production also contributes significantly to CO_2 emissions, with tea factories and gardens emitting substantial amounts. For instance, total CO_2 emissions from tea factory production in July 2021 reached 509,540.67 tones, while tea cultivation in the North-eastern states of India emitted 4,491.708 tones of CO2. The overall CO_2 emissions from tea cultivation and production in the same period summed up to 514,032.38 tones, with a discrepancy of 103,541.1 tones between CO_2 generation and sequestration by tea plantations. The reliance on fossil fuels and high-energy processes in the tea industry leads to heavy greenhouse gas emissions, especially from plucking, transportation, drying, and withering processes. Green tea shows high carbon emission intensities during consumption, processing, and cultivation. Packaging materials and logistics further add to the overall carbon footprint. To mitigate these impacts, the tea industry should adopt sustainable practices, such as using solar energy for drying, biodiesels and ethanol for transportation, and optimizing packaging materials. By implementing these measures, the tea industry can significantly reduce its carbon footprint and contribute to a more sustainable future, minimizing its impact on climate change.

Introduction:

Recently, organizations worldwide have become increasingly concerned about carbon credits, focusing on carbon emissions, the amount of carbon emitted by organizations, and the climate resilience of various systems. While there is considerable discussion about carbon sequestration, the topic of carbon footprints, which has become crucial, is often overlooked. It is very important for tea sector also to maintain a balance sheet in tea factories to measure the amount of carbon emitted and sequestered. Additionally, no carbon audits have been conducted. Although literature on carbon sequestration is available, studies on carbon footprints are limited. Some research has been conducted in China and other regions, but there has been no research on carbon footprints in Assam's tea industry to date. The concentration of CO_2 has increased significantly, rising from an annual average of 280 ppm in the late 1700s to 424 ppm in May 2023 (Aditya *et al.,* 2023). The agricultural sector contributes 15-20% of annual global greenhouse gas (GHG) emissions (FAOSTAT, 2018), with tea being an important agricultural product worldwide. The total planting area and yield of tea have been increasing in recent decades (Liang *et al.*, 2021). Tea production contributes to GHG emissions at various stages, from cultivation to consumption (Cichorowski *et al.*, 2015). The tea industry is considered to have high energy consumption due to its complex life cycle system (Zhang *et al.*, 2023). The production stage accounts for 57% of the environmental burden compared to other steps in the entire tea life cycle (Soheili-Fard *et al.*, 2018). In tea packaging, two-layer packaging is the most polluting scenario, while in terms of consumption, stoves are more environmentally friendly than electric kettles (Soheili-Fard *et al.*, 2018). Different farming management and processing techniques significantly impact the carbon footprint and primary energy demand of various tea products (Xu *et al.*, 2019). The carbon footprint of tea production and consumption is critical as it has substantial effects on the environment, economy, and society.

What is Carbon Footprint

A carbon footprint is a calculated value or index that makes it possible to compare the total amount of greenhouse gases that an activity, product, company or country adds to the atmosphere. Carbon footprints are usually reported in tonnes of emissions per unit of comparison (example: *tonnes* CO_2*-eq per year)*. A product's carbon footprint includes the emissions for the entire life cycle. These run from the production along the supply chain to its final consumption and disposal.

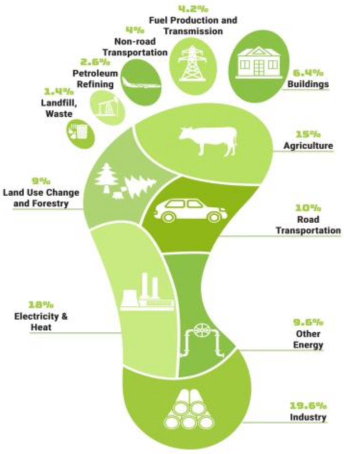


Figure 1: Carbon footprint illustration

Figure 1 shows the carbon footprint in different sectors. Highest footprint was found in industry (19.6%) 2nd highest in electricity and heat (18%) and 3rd one was in agriculture which is 15%

Types of Carbon Footprint

1. Individual carbon footprint

Carbon footprints based on individual use, take into consideration the GHG emissions associated with a person's chosen means of transportation, use of electricity at home, consumption of goods, eating habits, and recycling methods.

2. Product footprint

A product's footprint is the use of energy as it applies to all stages of production when it comes to creating a product. This includes GHG emissions from raw material extractions, various production processes, the generation of energy required, product alteration for companies, product use by customers, transportation between different stages, and all waste associated with it.

3. Corporate footprint

A corporate footprint includes an inventory of GHG emissions relating to the operations within an organization or a company.

It's one of the main ways to identify energy efficiency within an organization as well as results from joint efforts and collaborations with other companies in the sector.

Why is it Important in Tea?

Tea is one of the most widely consumed beverages and is cultivated on more than 3,691.89 hectares of land worldwide. As demand for tea continues to rise, the production chain consumes significant amounts of energy and materials to achieve higher yields in both cultivation and processing. This increased consumption of resources leads to unfavourable impacts on greenhouse gas emissions and contributes to climate change. Therefore, it is essential to assess the tea production system to identify its carbon footprint throughout its entire life cycle, from cultivation and processing to waste disposal.

Different Stages of Tea

- Production
- Processing
- Consumption

Different Operations in Tea Production

1. Land Preparation
2. Planting
3. Fertilizer Application
4. Pruning
5. Plant Protection
6. Plucking
7. Transportation

Land Preparation

Tea is a perennial plant, and once planted, the soil cannot be disturbed for the next 50-60 years, making proper land preparation essential. The preparation process differs for virgin areas and uprooted areas. In virgin areas, trees should be killed, uprooted along with their root systems, and the land should be levelled. In the case of uprooted areas, thorough ploughing and cross-ploughing should be carried out. Tractors are used for ploughing, and for larger areas, more than one tractor may be needed, leading to higher carbon emissions into the atmosphere.

Planting

For pit-making during planting, a number of laborers are involved, which contributes to carbon emissions.

Pruning

To form the bush frame, a series of pruning is carried out, involving laborers in the process. If machines are used instead, less labour will be required, but the machines will contribute more to carbon emissions.

Fertilizer application

Different types of synthetic fertilizers are applied in tea gardens, contributing to GHG emissions through runoff and leaching. Laborers are also involved in the process, which further contributes to carbon emissions.

Plant protection

Various chemical pesticides are applied in tea gardens to control pests and diseases, contributing to GHG emissions through runoff and leaching. Additionally, the involvement of laborers in this process further adds to carbon emissions.

Plucking

The harvesting stage, where tea leaves are plucked, is the most labour-intensive process, and therefore, it contributes more to carbon emissions compared to other operations.

Transportation

During transportation, from the garden to the factory, factory to warehouse, warehouse to auction house, and finally to the consumer, a significant amount of fossil fuels is burned, contributing substantially to carbon emissions.

Table 1: Operation wise fuel consumption & CO_2 produced in tea gardens

Farming Operations	**Fuel used (kg/ha)**	**kg CO_2 eq/ha**
Land development and planting	0.69	1.83
Irrigation	0.45	1.20
Fertilizer and chemical application	0.70	1.85
Pruning	0.89	2.35
Plucking and transportation	2.42	6.38

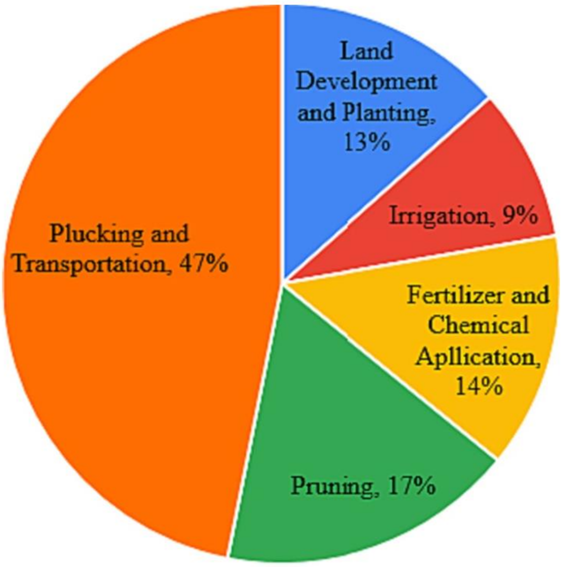


Figure 2: Operation-wise CO_2 produced in tea gardens in percent ((Aditya *et al.*, 2023)

Table 1 provides a breakdown of the fuel usage and associated carbon dioxide emissions across various farming operations in tea cultivation. Land development and planting consume 0.69 kg/ha of fuel, leading to 1.83 kg CO_2 equivalent per hectare. Irrigation uses 0.45 kg/ha of fuel, resulting in 1.20 kg CO_2 equivalent per hectare. Fertilizer and chemical application utilize 0.70 kg/ha of fuel, contributing to 1.85 kg CO_2 equivalent per hectare. Pruning operations use 0.89 kg/ha of fuel, emitting 2.35 kg CO_2 equivalent per hectare. The most fuel-intensive activity is plucking and transportation, which uses 2.42 kg/ha of fuel, resulting in the highest emissions at 6.38 kg CO_2 equivalent per hectare. Overall, plucking and transportation contribute significantly more to carbon emissions compared to other operations.

Figure 2 shows the highest carbon produced by plucking and transportation which is 47% of total carbon production of the garden.

Different Operations in Tea Processing

Figure 3: Steps involved in production of various varieties of tea ((Aditya *et al.*, 2023)

Different Operations in Tea Processing & Their Energy Consumption

1. Withering

- This process involves temporarily storing the harvested shoots to partially remove moisture, causes changes in the texture of the shoots & making the leaves flaccid
- Chemical changes that occur during withering contribute to the tea's flavour, aroma, colour, and taste
- Factory used equipment such as a centrifugal fan, heater, coal stove, axial fan, and withering trough for withering
- Estimated energy consumption for withering per 1,000 kg of made tea was 20.27 L of diesel, 43.93 kg of coal, and 87.17 kWh of electricity (Dutta *et al.,* 2019)
- For 100 kg of tea production, the specific electrical consumption required for withering was found as 5.54 kWh, and the required thermal energy was 179.11 MJ (Sharma *et al.,* 2019)

2. Rolling

- This operation imparts a specific shape and size to the withered leaves, resulting in a tea product that is acceptable to consumers
- There are two types of black tea produced based on the rolling method: Orthodox tea and CTC tea
- Factory used machines for rolling are rotor vane for CTC tea and table roller for orthodox tea rolling machine
- For 1,000 kg of made tea, the estimated electrical energy consumption for rolling was 190 kWh, and the thermal energy consumption was 574.63 MJ (Aditya *et al.,* 2023)
- Tea-processing units also rely on diesel generators for electricity during power cuts

3. Fermentation

- This process involves the oxidation of tea leaves
- Tea is classified into different types, including green, white, oolong, and black, based on the extent of oxidation
- Factory used equipment such as CFM machines, humidifiers, floor fermentation, fermenting troughs, electric fans, and blowers for fermentation
- Estimates of energy consumption for fermentation per 1,000 kg of made tea were 0.79 L of diesel and 89.65 kWh of electricity (Aditya *et al.,* 2023)
- Tea production of 100 kg, the required electrical consumption for fermentation was found as 8.63 kWh (Sharma *et al.,* 2019)

4. Drying

- Drying process is carried out to reduce the moisture content of the tea leaves to an appropriate standard (2.8%–3%) to halt enzymatic reactions and create a stable tea product
- It is one of the most energy- intensive processes in tea production
- For every 1,000 kg of made tea, the estimated energy consumption for drying is 16.08 litters of diesel, 630.22 kg of coal, and 103.41 kWh of electricity (Sharma *et al.,* 2019)

- In terms of thermal energy, the drying process requires 8.41 times more energy compared to the withering process (Sharma *et al.*, 2019) (Aditya *et al.*, 2023)

5. **Sorting and Packaging:**

- After the tea leaves have been dried, they undergo sorting, where any fibre and stalky substances are separated and the tea is sieved and graded based on particle size
- The final step in tea manufacturing is packaging, which is crucial for protecting the tea from moisture and contaminants
- These processes combined require an energy consumption of 61.72 kWh of electricity and 161.48 MJ of thermal energy per 1,000 kg of made tea (Aditya *et al.*, 2023)
- Energy requirements in these processes are comparatively lower than those in other stages of tea processing in factories

Table 2: Thermal and electrical energy requirements per 1000 kilogram of made tea & corresponding CO_2 emissions in tea factories at various stages of tea processing (Aditya *et al.*, 2023)

Operations	**Thermal energy (MJ)**	**Electrical energy (kWh)**	**kg CO_2 eq per 1,000 kg of tea made**
Withering	2837.16	87.17	475.39
Rolling	574.63	190.00	41.52
Fermentation	29.30	89.65	2.08
Drying	23868.68	103.41	**2762.28**
Sorting	134.00	53.15	9.52
Packaging	27.48	8.57	1.95

Table 2 shows the highest carbon footprint in drying process which is 2762.28 kg CO_2 eq per 1,000 kg of tea made.

Tea Consumption & Co_2 Emission

Factors influencing carbon emission in tea consumption are

1. Brewing Method
2. Energy Sour
3. Tea Type and Preparation
4. Packaging and Disposal
5. Additives
6. Frequency of Consumption
7. Waste Management

Brewing Method

1. Electric Kettle vs. Stovetop: The energy source and efficiency of the appliance used to boil water can significantly impact the carbon footprint. Electric kettles are generally more efficient than stovetop kettles

2. Quantity of Water: Boiling more water than necessary increases the energy consumption and, consequently, the carbon footprint.

Energy Sour

Carbon intensity of the energy source used for boiling water (e.g., coal, natural gas, renewable energy) plays a significant role. Regions with cleaner energy grids will have a lower carbon footprint for the same activity.

Tea Type and Preparation

Different types of tea (e.g., loose leaf, tea bags, instant tea) have different carbon footprints. Tea bags and instant tea often involve additional processing and packaging, which increase their overall carbon footprint

Packaging and Disposal

The type of packaging (biodegradable vs. non-biodegradable) and the disposal method (recycling, composting, landfill) affect the carbon footprint. Packaging materials that are not biodegradable or recyclable contribute to higher emissions.

Additives

Adding milk, sugar, honey, or other ingredients increases the carbon footprint. For example, dairy milk has a higher carbon footprint compared to plant-based alternatives.

Frequency of Consumption

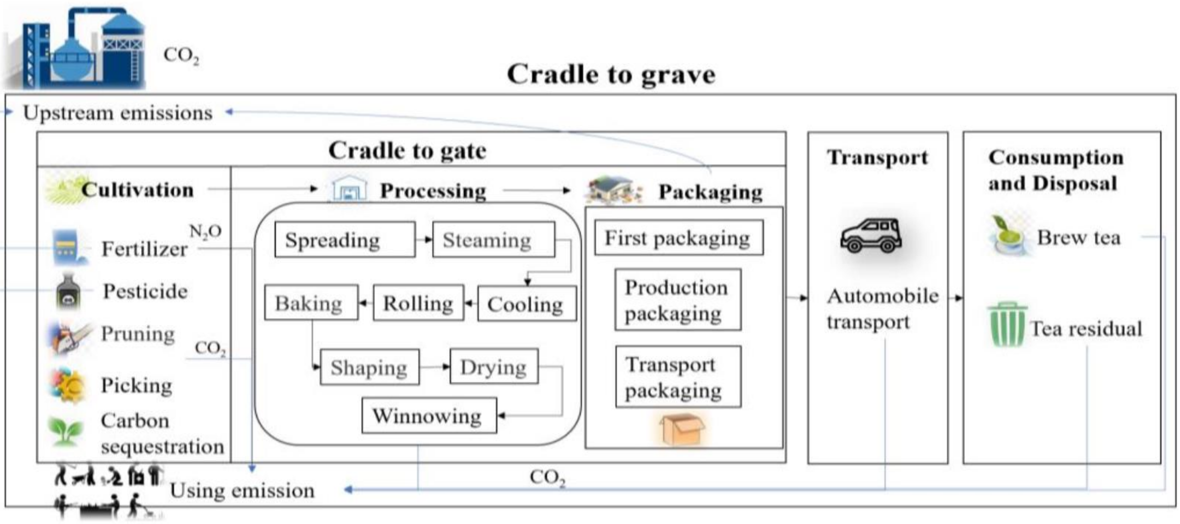
The frequency with which an individual consumes tea affects the cumulative carbon footprint.

Regular, heavy consumption will have a higher overall impact

Waste Management

The disposal of used tea leaves, bags, and any associated waste contributes to the carbon footprint. Proper composting or recycling can mitigate some of these impacts.

Carbon Footprint of Green Tea



The specific considerations for each stage are as follows:

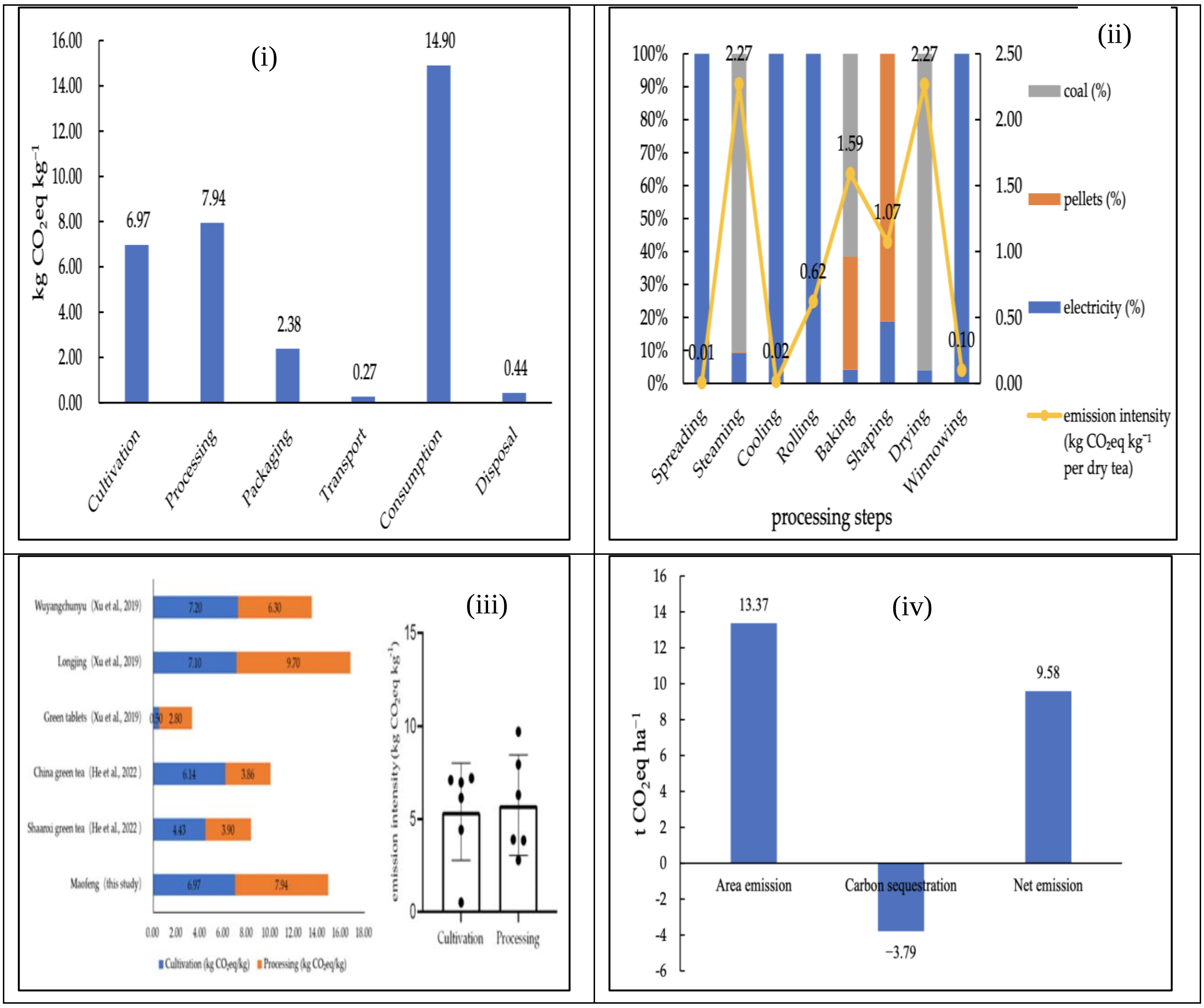
Cultivation: Emissions from the upstream production of fertilizer and pesticide, as well as emissions from fertilizer application in the field and the use of agricultural machinery in the pruning and harvesting period.

Processing: Emissions from electricity, coal, and pellets consumed by mechanical equipment in the processing stage

Packaging and transportation: Emissions from the production of packaging materials and energy consumption during transportation

Consumption and disposal: Emissions from boiling water and tea residue treatment (He *et al.*, 2023)

Results:



(He *et al.*, 2023)

Among the various farming operations, consumption exhibit the highest carbon footprint, significantly surpassing other operations. Within the processing stages of tea, steaming and drying have been identified as significant contributors to the overall carbon footprint. The use of coal during these processes further amplifies the emissions, making them the most carbon-intensive steps in tea processing. Additionally, when comparing the carbon footprint across different green tea products, both during cultivation and processing, noticeable variations are observed. Certain products demonstrate a higher carbon footprint, influenced by specific cultivation practices and processing methods. Finally, an analysis of the carbon balance in tea cultivation reveals a concerning trend. The carbon emissions are higher than the carbon sequestration rates, resulting in a positive carbon balance. This indicates that more carbon is being released into the atmosphere than is being absorbed, contributing to an increase in greenhouse gases and potentially exacerbating climate change.

Overall, these findings highlight the critical areas where interventions could reduce the carbon footprint of tea production, particularly in optimizing energy use during the most carbon-intensive stages and enhancing carbon sequestration practices.

Carbon Footprint & Carbon Sequestration

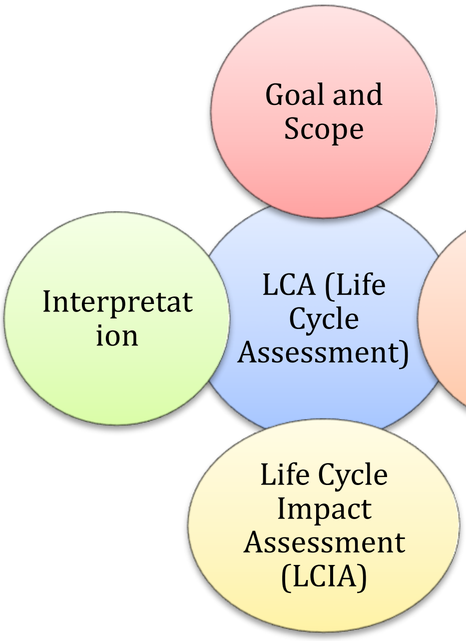
Tea bushes have shown significant potential in absorbing CO2, with a range of 1243.8–2526.7 kg CO_2/ha per year (Phukan *et al.,* 2018). Notably, higher-yielding tea cultivars demonstrate a greater capacity to assimilate CO_2 compared to those cultivars that focus more on quality production (Phukan *et al.,* 2018). Approximately 50% of the atmospheric CO2 absorbed by tea plants is sequestered within their biomass (Pramanik and Phukan, 2020). Moreover, tea bushes release organic carbon through their roots, equivalent to 5.9%–8.6% of the CO_2 they assimilate (Pramanik & Phukan, 2020). Mature tea bushes aged 25–30 years have been found to assimilate more CO_2 than younger plants, with an estimated sequestration of around 5134.4 ± 831.6 kg CO_2/ha per year in their biomass (Phukan *et al.*, 2018). The tea-albizzia plantation system has shown the highest potential for carbon offsetting (61.2 kg/plant) from the atmosphere, as well as carbon storage (33.66 kg/plant) both above and below ground (Alom *et al.*, 2021).

Continuous organic cultivation of tea plantations results in 43% higher above-ground biomass production (194.4 t/ha) compared to conventional systems (136 t/ha), with below-ground carbon accumulation recorded at 135 t/ha in organic plantations versus 125 t/ha in conventional systems (Subramanian *et al.,* 2013). For every ton of tea produced, tea factories contribute approximately 3,292 ± 493.91 kg of CO_2 emissions, while tea gardens contribute about 13.61 kg CO_2/ha (Kalita *et al.,* 2018). Within tea cultivation, the soil component holds the maximum proportion (80%) of carbon stock, followed by shade trees (11%), tea bushes (5%), and litter (4%).

In July 2021, total tea production from the North-Eastern states amounted to 157.23 million kgs (Tea Board of India, 2023), leading to total CO_2 emissions from tea factory production reaching 509,540.67 tonnes (Tea Board of India, 2023). The total tea crop area in the North-Eastern states covered 330,030 ha, resulting in a total CO2 emission of 4,491.708 tonnes during tea cultivation (Indian Tea Association, 2023). Collectively, the overall CO_2 emissions during cultivation and production in July 2021 summed up to 514,032.38 tonnes. The tea crop's atmospheric CO_2 sequestration in the same year, calculated using the algorithm, amounted to approximately 410,491.3 tonnes (Phukan *et al.*, 2022). This resulted in a discrepancy of 103,541.1 tonnes between CO2 generation through tea production and sequestration by tea plantations (Aditya *et al.*, 2023).

Assessing of Carbon Footprint in Tea

Life Cycle Assessment (LCA) is a systematic method used to evaluate the environmental impacts associated with all stages of a product's life, from raw material extraction through production, use, and disposal. This comprehensive approach is particularly useful in assessing the environmental footprint of tea production and consumption.



Goal and Scope

Objective: To understand the environmental impacts of tea production and consumption Scope: Includes all stages from raw material extraction (tea planting) to the end-of-life (disposal of tea leaves/bags)

Life Cycle Inventory (LCI)

•Data Collection: Gathering data on inputs (water, fertilizers, pesticides, energy) and outputs (emissions, waste) at each stage of the tea life cycle.

•Stages:

§ Cultivation: Use of land, water, fertilizers, and pesticides; emissions from soil

§ Processing: Energy used in withering, rolling, fermenting, drying, and packing

§ PackagingMaterials used, energy for manufacturing and transportation

§ Transportation: Fuel consumption and emissions from transporting tea to markets

§ Consumption: Energy used for boiling water, waste generated from packaging and tea residues

§ Disposal: Waste management practices for used tea leaves, bags, and packaging

Life Cycle Impact Assessment (LCIA)

•Impact Categories:

§ Global Warming Potential (GWP): Greenhouse gas emissions across all stages

Interpretation

- Results Analysis: Identifying stages with the highest environmental impacts
- Improvement Opportunities: Recommending actions to reduce environmental impacts, such as using renewable energy, optimizing resource use, and improving waste management practices

Conclusion:

The tea industry's reliance on fossil fuels and high-energy processes contributes substantially to greenhouse gas emissions. The plucking and transportation of tea leaves in tea gardens are major sources of carbon emissions, while the drying and withering processes during tea production have a significant global warming potential due to their electricity consumption. Green tea has high carbon emission intensities during consumption, processing, and cultivation, with packaging and boiling water further exacerbating its carbon footprint. It is crucial for the tea industry to adopt sustainable practices and energy-efficient technologies. Utilizing solar energy for drying, biodiesels and ethanol for transportation, and optimizing packaging materials can significantly reduce the industry's carbon footprint. By implementing these measures, the tea industry can move towards a more sustainable future, minimizing its impact on climate change.

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EGGSHELLS VALORISATION: FROM TANGIBLE SOLID WASTE TO POTENTIAL SUSTAINABLE RESOURCE-A MINI REVIEW

P. S. Chandel
Department of Chemistry,
Chintamani College of Arts and Science, Gondpipri
(Affiliated to Gondwana University, Gadchiroli)
Corresponding author E-mail: punmsc88@gmail.com

Abstract:

Urbanisation and industrialization projects work hand in hand, are expanding quickly, and are unavoidably important to overall economic progress. However, over time, these man-made activities cause a dreadful environmental decline. As a result, the quest for a practical remedy is essential and hastened. Adsorption is a cheap and straightforward method for removing harmful contaminants from water. Even more cost-effectiveness and sustainability can be achieved by the use of leftovers as adsorbents. In this review, using eggshells as an adsorbent in place of other solid residues is suggested. Eggshell is a biomineral with a high CaCO3 content that helps to bind heavy metals, fluoride, phenol, and other contaminants from contaminated soil and water. The eggshell had a porous structure, an intriguing surface area that was open to connect with the adsorbates, and a neutral surface charge at pH 7. It is mostly made of calcium carbonate. Because of its physicochemical features, it is researched and used in the fields of bioremediation, materials science, and metallurgy. The usefulness and environmental friendliness of this sorbent are increasing. The best method for removing hazardous metals is adsorption, particularly when the metal concentration is between one and one hundred parts per million (ppm) (Volesky, B, 2001). The cheap and simple regeneration of adsorbent makes biosorption effective. The present study analyses studies that include numerous eggshell recycling applications and usage during the past few years in the form of a low cost adsorbent for various treatments processes for removing chemicals from dyes, metallic ions, heavy metals that otherwise accumulate in the environment.

Keywords: Eggshell, Waste Biomineral, Solid Waste Management, Adsorption, Application of Eggshells, Natural Adsorbent, Sustainable Treatment, Low Cost Bioadsorption

Introduction:

Transformation of Eggshell-potential bio-waste into new value-added product with a more sustainably acceptable shape could yield significant environmental and financial benefits. Waste eggshells were utilised with a focus on low-cost adsorption to facilitate the widespread usage of unconventional adsorbents. Adsorbents that are affordable, cost-effective, and widely accessible should be employed to maximise the removal of hazardous elements overall. Eggshell powder

(ESP) is an affordable, effective adsorbent substance used to remove harmful heavy metals from water.

According to Valorization of Eggshell Biowaste for Sustainable Environmental Remediation 2020, global eggshell output would increase to nearly 90 million tonnes by 2030. (Scientific Reports, n.d.). The "circular economy" theory places a lot of emphasis on closing the loop for effective recycling rates along with the conversion of waste and byproducts into resources. The affluent nations have so far been able to prevent landfilling of this solid waste. According to studies and reviews, there are two categories of uses for industrial eggshell waste: Category 1 - "Raw material" uses include food additives, soil amendments, purified calcium carbonate, cosmetics, and biomaterial composite; and Category 2 - "Operating supply" uses include using it as a catalyst or sorbent, both of which have significant positive effects on the environment. (Industry application). Eggshell can be utilised as a fertiliser, an animal feed ingredient, a biodiesel catalyst, a calcium deficiency remedy, and to immobilise and fix heavy metals in contaminated soil, according to research investigations conducted over the previous ten years (trash to treasure). In the near future, a variety of useful final goods may be produced from tangible wastes like eggshells (Silvano Mignardi *et al.,* 2020). By utilising limestone as a benchmark, the ability of chicken eggshell waste to make calcitic lime was investigated. This revealed that calcium oxide from eggshell waste belonged to the most reactive class (R5—60 °C after 10 min) (Eduardo Ferraz *et al.,* 2018). Eggshell waste served as a starting point for the creation of catalysts for the partial oxidation of methane. By impregnating calcined eggshell surfaces with copper, catalysts were created. These surfaces made good catalyst supports for metals to be used in oxidation reactions. When Pb2+, Cd2+, and Cu2+ were removed from aqueous solutions using eggshell and coral wastes, it was discovered that the adsorption of the heavy metals was H-type at low initial concentrations, indicating strong adsorbate-adsorptive interactions, whereas at high initial concentrations, the metal adsorption was described by an L-type isotherm. The selectivity sequence in eggshell wastes was discovered to be Pb2+ > Cu2+ > Cd2+ based on the distribution coefficient (Kd) and metal removal % values. According to the results, ESP could be employed as a low-cost, long-lasting, and efficient adsorbent for Cd2+ removal in aqueous solutions from a variety of effluent sources. (chkn eggshell potential for the environment) Pesticides, heavy metals, and phenolic compounds from contaminated soil and wastewater are also absorbed thanks to its high absorbent capacity (Carvalho *et al..,* 2011). Eggshells don't require surface pretreatment or activation because of their inherently porous structure, abundant fibrous protein, and normal chemical makeup of 2% organic and 98% inorganic chemicals, which also readily permits gaseous exchange (Pettinato, 2015). Additionally, research have revealed that milling is advantageous for ES. (Balá *et al.,* 2016). The best results were achieved using the optimum ratio of 2:8, which improved the mechanical characteristics of recycled paper. Eggshell fibre waste combination paper versus waste paper had the highest tensile strength (Owuamanam & Cree, 2020). When compared to the control samples under observation, it was discovered that calcium chloride derived from eggshell extended the shelf life of fresh cut fruits to 15 days. Studies have shown that eggshell waste has a wide range of uses. For example, this biomineral can be used to (a) reduce biodiesel pollutants by acting as a solid base catalyst, making the production of biodiesel completely ecological, economical, and environmentally friendly; or (b) remove heavy metals from wastewater or metal-contaminated soil, addressing a serious environmental issue that is caused by industry. (c) as a biomaterial to replace bone tissues in osteoporosis patients; (d) as a calcium supplement and fertiliser in the diet of higher organisms. In order to precipitate out divalent lead cations from aqueous solutions in the slightly acidic pH range, waste eggshells were employed as an addition (Vijayaraghavan & Joshi, 2013). Waste eggshells were used as a reactor system in an unique bioinspired synthetic method for the controlled synthesis of nanostructures produced on various substrates. According to studies, eggshell waste acts as a catalyst, cofactor, facilitator, and more in a variety of synthetic reactions. In 2010, Sharma *et al.* using calcined hen eggshells, 95% of the pongam tree oil used to make biodiesel (alcohol/oil ratio: 8:1, catalyst: 2.5 wt%) was successfully converted into the fuel. Similar research was done in 2015 by Suprathi B. Chavan, Rajendra R. Kumbhar, D. Madhu, Bhaskar Singh, and Yogesh C. Sharma (Synthesis of biodiesel from Jatropha curcas oil using waste eggshell and analysis of its fuel characteristics). Jatropha curcas oil was converted into biodiesel (yield: 90%) using calcium oxide as a catalyst and eggshell waste as a source of calcium. At a temperature of 60 C and 1.7% (v/v) H2SO4, the catalyst functioned effectively up to 6 times without experiencing a substantial loss of activity. The ideal methanol/oil molar ratio was maintained at 8:1. Using a mixture of seashell and eggshell complexed with TiO_2 as the catalysing agent, biodiesel production from Jatropha oil produced 95% with a methanol/oil molar ratio of 20:1 and 10% catalyst at 140-190 C and 60-80 pressure (Semwal *et al.,* 2011; Olutoye *et al.,* 2011). Eggshell modified with magnesium and potassium nitrates was employed as a catalyst for the transesterification of palm oil at 65 degrees Celsius, yielding 65% at 5.3 weight percent catalyst, a methanol/oil molar ratio of 16:1, and a reaction duration of 4.6 hours with up to three catalyst recyclings (Memthong *et al.*, 2012). Utilising microwaves and a solid CaO catalyst obtained from used eggshells, improved biodiesel synthesis was accomplished in comparison to conventional heating. At the optimum settings of 4 min of reaction duration, 900 W of microwave power, 18:1 methanol/oil ratio, and 15% catalyst, it produced 96%. With cooking oil and eggshell catalyst, late researchers. Navajas *et al.* (2013) achieved 100% biodiesel yield (60 C, 5 h, 24:1 methanol/oil ratio, and 4 wt% catalyst).

By using KF modification and thermal treatment to create an eggshell catalyst, Zeng *et al.* (2015) demonstrated that it could be used up to 10 times with a yield of >80% (catalyst 2 wt%, methanol/oil molar ratio 12:1, and 65 C). In order to transesterify palm oil, Chen *et al.* (2015)

created a hybrid catalyst called CaO-SiO2 from eggshell and Na2SiO3. As the proportion of Si compounds in the catalyst's composition increased, its catalytic activity decreased while its reusability increased. In the same line of research, he developed catalysts with the maximum activity using 30% and 70%, respectively, of calcined eggshell and calcined rice husk. He also employed rice husk ash and a calcined eggshell. The biodiesel yield was determined to be 91.5% using a methanol/oil molar ratio of 9:1, a reaction period of 4 h, and a catalyst loading of 7 wt%. After 8 cycles of reuse, the biodiesel yield was above 80%. Taufiq-Yap and others (2013). Eggshell waste has been employed as a catalyst for the gasification of waste wood to produce hydrogen. Azadirachta excelsa wood was gasified as biomass using a CaO catalyst made from eggshells. Eggshells and numerous substances have produced fantastic outcomes. Research has been done on the impact of a composite catalyst (K_2CO_3 and CaO generated from ES) on coal gasification. By utilising such composite catalysts, greater volumes of H2 and CO were created, and the yields increased by 6% and 123%, respectively. Due to its biodegradability, low bioaccumulation, and low toxicity, DMC, a methylating and carboxylating agent as well, has been sought after for greener route processes. It was synthesised by Gao and Xu using an eggshell-derived catalyst (2012). Chromenones, specifically 2-amino chromenes, which are bioactive compounds with numerous applications in the pharmaceutical sector, agrochemicals, cosmetics, and pigments, among other fields (Kachkovski *et al.*, 2004), have been created using eggshells. Additionally, it was discovered that sonicated eggshell effectively catalysed the reaction with up to six times reusability. Eggshells were employed as a catalyst by (Mosaddegh and Hassankhani, 2013) to create 7,8-dihydro-4H-chromen-5(6H)-ones at room temperature with up to five times the reusability. The production of solely alkene 5 and neither 2-amino-chromenes 4 nor 7,8-dihydro-4H-chromen5(6H)-one 4 was used by the authors to demonstrate the reaction's selectivity. According to Morbale *et al.*, eggshell has a crucial impact on the reaction's selectivity (2015). The production of 1,4-dihydropyridine and polyhydroquinoline, which are known to have various biological functions, was catalysed by modified eggshells (antitumor, anti-inflammatory, antitubercular and analgesic). According to Stone *et al.* (2007), benzothiazoles have antitumor, antibacterial, anticancer, and antidiabetic properties. Borhade and others (2016) The production of 2-arylbenzothiazoles in a single pot involved the use of o-aminothiophenol in a reaction with variously substituted aromatic aldehydes and calcined eggshell that had been ground without the use of any solvent at room temperature. Due to its commercial viability in the food and pharmaceutical industries, o lactulose, a bioactive molecule, has recently attracted growing interest. The body uses lactulose for a variety of purposes, including the decrease of blood ammonia and serum lipids, the prevention of gallstone formation, the regulation of blood glucose and insulin, the relief of constipation, the stimulation of mineral absorption, and the prevention of cancer (Panesar and Kumari, 2011; Seo *et al.,* 2016; Nooshkam and Madadlou, 2016). By isomerizing lactose, lactulose can be created. Using raw eggshell as a catalyst, Montilla *et al.* (2005) studied the effects of catalyst loadings, lactose concentration, and pH on the production of lactulose through isomerization of lactose. After 90 minutes at 98 C and utilising 4 mg/mL of catalyst, the maximum lactulose production from milk permeate was around 25%. Similar methods were used by Nooshkam and Madadlou (2016) to generate lactulose using milk ultrafiltration permeate. According to Nasrollahzadeh *et al.* (2016), waste eggshells were used to create Cu/eggshell, Fe3O4/eggshell, and Cu/Fe3O4/eggshell nanocomposites. High catalytic efficiency was demonstrated by these metallic nanocomposites in the removal of several colours from aqueous solutions. Even after seven re-uses, these catalysts have been regenerated and reused with great efficiency. Calcium zeolite type A (CaNaAlSi2O7) was created using CaO that was created by pyrolyzing chicken eggshells (Tangboribooron *et al.*, 2011) The average pore diameter was 37.19 nm, and the specific surface area was 55.15 m2/g, which is equivalent to commercial zeolites. The authors proposed their use as an adsorbent in the treatment of wastewater due to its extensive use as a catalyst, ion exchanger, or molecular sieve. (link-A evaluation of eggshell waste as catalyst) Due to the surface functionalization of biowaste eggshell, composites based on acrylonitrile butadiene rubber (NBR) and supplemented with ES and $CaCO_3$ microfillers at varied loading levels were shown to have improved mechanical characteristics. The edge of the eggshell over calcium carbonate in acrylonitrile butadiene rubber is described in "The Taste of Waste." The availability of the metals was investigated as well as the efficiency of eggshell waste in immobilising Cd and Pb. Models for comprehending their adsorption quality and capability have been used to study the use of eggshell waste for the removal of organic dyes and heavy inorganic ions. (A review of ultrastructure, biomineralization, and other uses for sorption on eggshell waste.) Eggshell's adsorption capabilities for Remazol dye removal from wastewater were investigated under ideal conditions. (Eggshell Waste Biosorbent Adsorption of Remazol Brilliant Violet-5R Textile Dye from Aqueous Solutions).

Conclusion:

After a thorough examination of how eggshells have been used over the past few years, it has come to light that eggshell waste is a biomineral rich in calcium compounds, which are themselves promising components in a variety of composites, building materials, heavy metal adsorbers that don't need preactivation, and catalysts in numerous organic and inorganic heterogeneous reactions. As a scalable alternative for the commercial calcium compounds utilised in the situations above, eggshells might be employed sustainably. In addition to this, research on more recent eggshell hybrids for desired varied functioning can be done. It offers enormous promise for water remediation when combined with a first-rate waste management strategy. Utilising eggshell trash has potential in the circular economy for managing solid waste.

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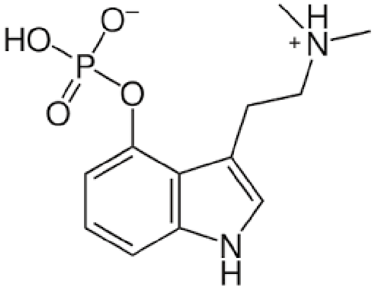
PSYCHOACTIVE MUSHROOMS: NATURE'S HALLUCINOGEN

Lakshmi Girish
Smt. Chandibai Himathmal Mansukhani College, Ulhasnagar, Maharashtra, India.
Corresponding author E-mail: lakshmig7503@gmail.com

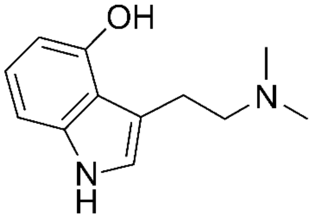
Introduction:

The fruiting body of basidiomycetes fungi are known as mushrooms. Studies have been conducted on the nutritional, medicinal, and culinary properties of mushrooms. Psychoactive or magic mushrooms, often known as hallucinogenic mushrooms (Nichols, 2016), are one of the most widely used natural hallucinogens in the world because of their easy production and vast geographic distribution (Stafford, 2013). Publications from various countries such as Canada, U. S, Mexico, South America, Europe, India, Japan, New Guinea, and Australia suggest its worldwide distribution (Matsushima, 2009). Psychedelic mushrooms have been utilized since thousands of years for both therapeutic and ceremonial purposes (Guzman, 2008). The main genera include *Psilocybe, Panaeolus, Gymnopilus, Copelandia, Hyboloma, Pluteus, Inocybe, Conocybe, Stropharia* and *Panaeolina.* Guzman *et al.* (1998) recorded four groups of psychoactive mushrooms: those that produce psilocybin and psilocin, those that produce ibotenic acid and muscimol (*Amanita muscaria* and *Amanita pantherine),* those that produce ergot alkaloid *(Claviceps purpurea*, and *Cordyceps),* and the last group that has not been the subject of reliable chemical research or the identification of its active ingredients. More than one hundred species of hallucinogenic mushrooms exist, out of which the most well-known and extensively researched species is *Psilocybe cubensi.*

The psychotropic substances such as Psilocybin and Psilocin have the power to significantly change perception, mood, and mental processes of the people who consume them. A first comprehensive report on magic mushrooms was published in the magazine Life in 1957 by Gordon Wasson and Valentina. This work is followed by Albert Hofmann, who reported LSD (Lysergic Acid Diethylamide), isolated psilocybin and psilocin from Psilocybe Mexicana. Further research on magic mushrooms was sparked by the work of these ethnomycologists.



Psilocybin



Psilocin

(Images credit: Images are taken under creative common licence)

Morphologically, psychedelic mushrooms are generally small, brown to white that turn bluish to black when the tissue is injured or disturbed (Guzmán, 2008). When psilocybin is exposed to oxygen, an oxidative process occurs that produces the blue stains (Lenz *et al.*, 2020).

Psychedelic mushrooms mostly contain a serotonergic hallucinogenic prodrug called psilocybin. After being ingested, magic mushrooms are broken down in the stomach and their active components may undergo partial modifications in the liver (for example, psilocybin is dephosphorylated to psilocin), after which they are transported to the heart and circulated to the brain. Like LSD, psilocin acts on the brain by increasing serotonin (5HT-2A), a neuromodulator that regulates other neurotransmitters and influences mood, perception, memory, awareness, and appetite, among other mental processes (Nichols, 2016). According to Reiff *et al.* (2020), psilocybin is non-addictive and offers both short and long-term benefits for treating mood disorders, abuse disorders, and chronic pain. Psychoactive mushrooms belong to the category of central nerve poisoning (Kamimura, 1999). According to Matsushima *et al.* (2009), these mushrooms cause central nervous and physical symptoms, the effects of which are usually transient. Prefrontal cortex of the brain influences perception, thought, and mood. Psilocybin activates the serotonin receptors in this region. According to the European Monitoring Centre for Drugs and Drug Addiction (EMCDDA), the effects typically begin within 20 to 40 minutes and can last between 4 to 6 hours. After that, the liver metabolizes psilocin, which is then eliminated through urine. The toxicity profile of psychoactive mushrooms is mild in comparison to several other hallucinogens.

Effects of Psychoactive Mushrooms

Psilocybin mushrooms have diverse effects on different persons in different settings at different times (Studerus *et al.* 2012). Psychoactive mushrooms can provide a wide range of effects, from mild euphoria to intense experiences of mysticism. Common side effects include deep introspective and philosophical thoughts, auditory and visual hallucinations, and altered sense of time. The short-term effects of the drug include sensory enhancement, sense of time changing, flowing patterns and shapes, unusual thoughts and speech, personal insight and reflection, and excited mood (Shulgin and Alexander, 1980). The peak effect of the drug is visible after 2-3 hours after ingestion. Research indicates that long-term physical effects of psilocybin may be the result of preexisting mental health conditions. The degree of the physical impacts varies from person to person. The symptoms that occur most commonly are mild to moderate and believed to be side effects of emotional intensification. These reactions include dilated pupils, higher blood pressure, and accelerated heart rate. However, these may occasionally result in psychological symptoms such as anxiety, panic attacks, paranoia, and mood swings, along with other reported symptoms like nausea, increased sweating, numbness, and tremors (Carbonaro *et al.* 2016).

(A) *Psilocybe semilanceata*, (B) *Psilocybe chuxiongensis*, (C) *psychedelic Psilocybe stuntzii* (white arrow) (D) *Panaeolus cyanescens*, (E) *Panaeolus axfordii,* (F) unidentified *Psathyrella,* (G) *Pluteus cervinus*, (H*) Pluteus cyanopus*, and (I) *Pluteus salicinus* (J) *Gymnopilus liquiritiae* (K) *Armillaria mellea* (L) *Gymnopilus spectabilis*

Images credit: Strauss *et al.* (2022).

Legal Status

Around the world, psychedelic mushrooms have different legal status. In many countries, they are classified as Schedule I substances, making their use, possession, and distribution illegal. Nonetheless, some countries have decriminalized its use or permit use under strict guidelines with a special license from the Drug Enforcement Administration.

Since mushrooms are living and naturally contain psilocin and psilocybin, they are usually regarded as legal substances. According to Russell Newcombe (2004), this is because they are drugs, which are "a naturally occurring substance." However, if these substances are chemically synthesized, they are classified as Class A controlled substances, making it illegal to supply or possess them.

Therapeutic Potential

The monitored and controlled use of Psilocybin may help to treat a variety of mental illnesses, spiritual and psychological growth, and enhanced creativity (Nicholas, 2004). Henry *et al.* (1996) reported the use of hallucinogens to recover suppressed memories for the treatment of alcoholism, antisocial conditions, depression, schizophrenia, autism, and obsessive-compulsive disorder. Psilocybin is effectively used in the treatment of addiction, PTSD, anxiety, end-stage cancer, and mood disorders. Clinical trials have demonstrated that psilocybin-assisted therapy can lead to significant and lasting improvements in patients. Psilocybin was considered as a promising treatment by psychiatrists, scientists, and mental health professionals as an adjunct to therapy for a wide variety of psychiatric illnesses (Grinspoon *et al.* 1979).

Conclusion:

An insight into the complex connections between the mind, brain, and environment is offered by psychoactive mushrooms. Even while there are certain risks involved, their potential advantages especially in therapeutic uses are becoming more widely appreciated. As research progresses these ancient mushrooms may hold the key to opening fresh avenues for treating mental illness and comprehending human consciousness. The correct identification of psychedelic mushrooms from their toxic species can be facilitated by molecular sequencing. There is a great scope for further investigation into exploiting these mushrooms to treat various kinds of mental disorders in humans.

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HOLISTIC STRATEGIES FOR MITIGATING GLOBAL CLIMATE CHANGE: ESSENTIAL CHANGES IN HUMAN LIFE

Suresh Kumar K A
Department of Botany,
Government College Chittur, Palakkad, 678 104 - Kerala, India.
Corresponding author E-mal: sureshtvmala74@gmail.com

Abstract:

Global climate change presents an unprecedented challenge, necessitating urgent and significant alterations in human behaviour, social structures, and scientific and technological advancements. The adverse effects of climate change, such as extreme weather events, rising sea levels, and qualitative and quantitative biodiversity degradation, endanger life on Earth. Mitigating this crisis requires a holistic and sustainable approach encompassing human lifestyle changes, economic transformations, policy reforms, technological innovations, educational advancements, ecosystem protection, and social justice. The essential changes in human life to address climate change, emphasizing the interconnectedness of these strategies. Key areas include adopting sustainable and eco-friendly lifestyles, transforming economic systems towards green economics and carbon pricing, enhancing policy and governance with international cooperation and urban planning, promoting technological innovation in renewable energy and sustainable agriculture, fostering environmental education and awareness, protecting and restoring ecosystems, and ensuring equity and climate justice. Through collective efforts in these domains, humanity can mitigate and adapt to the impacts of global climate change.

Key words: Climate Change, Sustainable Lifestyles, Carbon Footprint, Food Miles, Green Economy, Renewable Energy, Policy Reforms, Environmental Education, Ecosystem Protection, Climate Justice, Carbon Pricing, Biodiversity Conservation.

Introduction:

Global climate change is an unprecedented challenge that urge us an immediate and profound transpose in human behaviour, societal structures, and scientific technological advancements. The consequences of climate change, including extreme weather events, rising sea levels, and degradation of biodiversity, endanger the very foundations of life on the blue planet, the Earth. Addressing this crisis requires a holistic approach encompassing lifestyle changes, economic transformations, policy reforms, technological innovations, educational advancements, ecosystem protection, and social justice. The essential changes needed in human life to alleviate and adapt to the impacts of global climate change, emphasizing the interconnectedness of these changes.

1. Adopting sustainable lifestyles

Adopting sustainable lifestyles is the keystone of individual contributions to climate change alleviation. This encompasses several critical areas:

- **Reducing carbon footprint:** One of the most effective ways individuals can combat climate change is by reducing their carbon footprints. This can be achieved through various measures such as opting for public transportation, cycling, or walking instead of driving personal vehicles. Reduced food miles or eat miles (distance food has travelled to get to your plate) is the concept related to carbon footprint. Food miles is the distance food is transported from the time of its making until it reaches the real consumer. Food miles or eat miles is one factor used when testing the environmental impact of food, such as the carbon footprint of the food. The concept of food miles originated in United Kingdom in early 1990s. Additionally, reducing air travel, carpooling, and investing in fuel-efficient or electric vehicles can significantly cut down greenhouse gas emissions. Simple actions like turning off lights when not in use, using energy-efficient appliances, and insulating homes can also contribute to energy conservation.
- **Sustainable diets:** The food we consume has a substantial impact on the environment. Adopting a more plant-based diet and reducing meat consumption can lower the carbon footprint associated with food production. (The 10% rule in food chains, also known as Lindeman's trophic efficiency rule, states that only 10% of energy is passed from one trophic level to the next in a food chain. The remaining 90% of energy is lost as heat or used for growth and reproduction). Livestock farming is a major contributor to methane emissions, a potent greenhouse gas. By choosing locally-sourced, organic, and seasonal produce, individuals can further reduce the environmental impact of their diets.
- **Minimizing waste:** Reducing, reusing, and recycling materials can help decrease the amount of waste that ends up in landfills, which produce methane as organic waste decomposes. Composting organic waste, avoiding single-use plastics, and supporting products with minimal packaging are practical measures to minimize waste. Zero waste management is the output the thoughts in this direction.
- **Water conservation:** Water is elixir of life on the earth that needs to be conserved.It is the blue gold in the blue panet. Simple actions like fixing leaks, using water-efficient fixtures, and adopting water-saving practices in daily life can make a significant difference. Collecting rainwater and using it for gardening or other non-potable purposes is another effective conservation strategy.

2. Transforming economic systems

The current economic systems often prioritize short-term gains over long-term sustainability. Transforming these systems to support a green economy is essential for mitigating climate change:

- **Green investments:** Redirecting investments towards renewable energy like solar energy, wind and wave energy, geothermal energy, gravitational energy etc. sustainable agriculture, and green technologies can foster innovation and reduce reliance on fossil fuels. Recent advancements in cold fusion (fusion of light weight atoms at normal temperature and pressure) are igniting new hopes and raising expectations in this field. Governments and financial institutions should incentivize green investments and disincentivize investments in fossil fuels.
- **Carbon pricing:** Implementing carbon pricing mechanisms, such as carbon taxes or cap-and-trade systems, can incentivize businesses to reduce their carbon emissions. By putting a price on carbon, these mechanisms encourage industries to adopt green technologies and eco-friendly practices.
- **Sustainable business practices:** Encouraging businesses to adopt sustainable or ever green practices, such as using eco-friendly materials, reducing energy consumption, and ensuring ethical supply chains, is crucial. Corporate responsibility and sustainability reporting should be mandatory. Businesses should be encouraged to implement circular economy principles, where waste is minimized, and products are designed for reuse, recycling, or composting.
- **Supporting green employment:** The transition to a green economy will create new employment opportunities in renewable energy, energy efficiency, sustainable agriculture, green tourism and other sectors. Governments should invest in training and education programs to empower workers with the skills needed for these novel emerging fields.

3. Enhancing policy and governance

Governments play a pivotal role in combating climate change through effective policies and regulations:

- **International agreements:** Strengthening international agreements like the Paris Agreement is essential for global cooperation in reducing greenhouse gas emissions. Countries in the world must commit to more ambitious targets and ensure compliance. International cooperation and understanding is also necessary for technology siphoning, capacity building, and financial support to developing and underdeveloped countries from developed countries and international organisations.
- **National legislation:** Countries need to implement stringent environmental regulations, including emissions standards, renewable energy mandates, natural resource management and deforestation controls. Providing incentives for renewable energy adoption and penalizing polluters are effective strategies. Governments should also develop and implement national adaptation plans to enhance resilience to climate impacts.
- **Urban planning:** Towns should be designed to be more sustainable, with efficient public transport systems, vehicle sharing system, green spaces, and infrastructure that supports

renewable energy. Smart city initiatives that incorporate energy-efficient buildings (green construction), waste management systems, and sustainable transportation can significantly reduce urban carbon emission. Policies should promote high-density, mixed-use development to reduce urban sprawl and preserve natural landscapes.

- **Protecting natural resources:** Governments should implement policies to protect, conserve and restore natural resources, including forests, wetlands, and oceans. This includes enforcing anti-deforestation laws, promoting reforestation, and protecting marine, estuarine and fresh water ecosystems from pollution and overfishing.

4. Promoting technological innovation

Technology offers numerous solutions to alleviate global climate change:

- **Renewable energy technologies:** Investing in solar, wind, hydro, gravitational and geothermal energy can reduce dependence on fossil fuels. Technological advancements in energy storage, such as batteries, are essential to overcome the intermittent nature of renewable energy. Governments and private institutions should support research and development in renewable energy technologies.
- **Energy efficiency innovations:** Developing energy-efficient appliances, buildings, and industrial processes can significantly cut down energy consumption. Innovations in building materials, insulation, and smart grid technologies can enhance energy efficiency. Governments should set energy efficiency standards for appliances, vehicles, and buildings.
- **Carbon Capture and Storage (CCS):** Investing in technologies that capture and store carbon dioxide emissions from industrial sources can help mitigate climate change. Research into direct air capture (DAC) technologies is also crucial. These technologies can be used in combination with renewable energy to achieve negative emissions.
- **Sustainable agriculture:** Technological advancements in sustainable farming practices, such as precision agriculture, vertical farming, polyhouse farming, promotion of cultivation of millets which can grow in arid and semi-arid condition with less utilisation water and genetically modified crops that require fewer resources, can reduce the environmental impact of food production. Innovations in soil health management, water-efficient irrigation, and agroforestry can enhance the sustainability of agriculture. Awareness creation on virtual water
- **Virtual water:** Virtual water (also called indirect water or embedded water) use refers to the water used to produce the goods and services others need and enjoy. For example, think about the water needed to make a box of cereal so you can enjoy a bowl of corn flakes? For example, think about the water needed to make a box of cereal so you can enjoy a bowl of corn flakes? The flakes are crispy and dry, so they may wonder how water is involved at all. To grow, manufacture and package food products such as corn flakes takes a huge

amount of water. The corn was almost certainly irrigated while it was being grown, and the factory that manufactures the flakes used water in almost every step of the process, from cleaning the corn before the manufacturing process started to rinsing away what was left behind. Even the paper box that holds the flakes required large quantities of water to produce.

- **Green transportation:** The development and adoption of electric vehicles (EVs), hydrogen fuel cells, and other low-emission transportation technologies are critical. Investing in public transportation infrastructure and encouraging the use of non-motorized transport, such as cycling and walking, can further reduce emissions from the transportation sector. Large reserves of energy savings for transportation are the use of more economical inland waterway transport. The experience of many countries shows that the cost of water transport is almost four times cheaper than railway and road transport

5. Fostering environmental education

Raising awareness and educating people about the importance of environmental protection is vital for fostering a culture of sustainability:

- **Educational curricula:** Incorporating climate change and environmental studies into educational curricula at all levels can inculcate a sense of responsibility in future generations. Schools, colleges and universities should offer programs and courses on sustainability, environmental science, and renewable energy, waste management etc.
- **Public awareness campaigns:** Governments, NGOs, and media outlets should run campaigns to inform the public about the impacts of climate change and the importance of sustainable practices. Social media, documentaries, and community events can be effective tools for raising awareness.
- **Community engagement:** Local communities should be involved in environmental protection initiatives, such as tree planting drives, clean-up campaigns, and conservation projects. Grassroots movements can drive significant change at the local level. Community-based adaptation and mitigation projects can enhance resilience and promote sustainable development.
- **Corporate Social Responsibility (CSR):** Businesses should engage in CSR activities that promote environmental sustainability. This includes reducing their own environmental impact, supporting environmental projects, and raising awareness among employees and customers.

6. Protecting and restoring ecosystems

Ecosystems play a critical role in regulating the climate. Protecting and restoring these natural systems is essential:

- **Forest conservation:** Forests act as carbon sinks, absorbing significant amounts of CO_2 from the atmosphere. Protecting existing forests from deforestation and promoting afforestation and reforestation efforts are vital. Sustainable forest management practices, such as selective logging and agroforestry, can balance economic needs with conservation.

- **Wetland protection:** Wetlands store carbon and provide crucial ecosystem services, including water filtration, flood control, and habitat for wildlife. Protecting and restoring wetlands can enhance their ability to mitigate climate change. Policies should protect wetlands from drainage, pollution, and development.
- **Ocean conservation:** Oceans absorb a large proportion of CO_2 emissions. Protecting marine ecosystems from pollution, overfishing, and habitat destruction is necessary to maintain their carbon sequestration capabilities. Marine protected areas (MPAs) can safeguard critical habitats and biodiversity.
- **Biodiversity conservation:** Biodiversity is essential for ecosystem resilience and stability. Protecting endangered species, conserving habitats, and promoting sustainable land use practices can enhance biodiversity and ecosystem health. Conservation efforts should consider the impacts of climate change and prioritize actions that enhance the adaptive capacity of species and ecosystems.

7. Equity and climate justice

Addressing climate change requires a focus on equity and climate justice:

- **Supporting vulnerable communities:** Climate change disproportionately affects vulnerable communities, including those in developing countries and marginalized groups. Providing support through adaptation measures, financial aid, and capacity building is essential. International cooperation and climate finance are critical to support adaptation and mitigation efforts in developing countries.
- **Fair transition:** Ensuring a fair transition for workers in industries that are phased out as we move towards a green economy is crucial. Job training and social support systems can help mitigate the economic impacts on these workers. Policies should promote social equity and inclusion in the transition to a low-carbon economy.
- **Inclusive policy making:** Policies should be inclusive and consider the voices of all stakeholders, especially those most affected by climate change. Participatory governance can enhance the effectiveness and fairness of climate policies. Indigenous peoples, women, youth, and other marginalized groups should be involved in decision-making processes.
- **Gender equality:** Women are disproportionately affected by global climate change but also play a crucial role in climate action. Promoting gender equality and empowering women can enhance the effectiveness of climate policies and actions. Gender-responsive approaches should be integrated into climate mitigation and adaptation strategies. Green belt movement in Kenya lead by Wangari Maathai, Bishnoi movement in India lead by Amrita Devi Bishnoi,

Conclusion:

Mitigating global climate change demands an interconnected, comprehensive approach that addresses lifestyle changes, economic transformation, policy reform, technological explosion, education, ecosystem conservation, and social justice. Each of these domains is unique and plays a critical role in fostering a sustainable and resilient future. Adopting sustainable lifestyles reduces individual carbon footprints, while transforming economic systems supports long-term environmental health. Enhanced policies and governance create frameworks for effective action, and technological innovations provide the tools needed for a green transition. Education and awareness raise collective consciousness, empowering communities to act. Protecting and restoring ecosystems ensures the natural balance necessary for climate regulation, and addressing equity and climate justice ensures that the most vulnerable are supported in this global endeavour.

By integrating these strategies and recognizing their interconnected nature, humanity can not only mitigate the adverse effects of climate change but also create a more just and sustainable world. The collaborative effort of individuals, businesses, governments, and international bodies is essential in this transformative journey. Together, we can safeguard our planet for future generations, ensuring a thriving environment for all life on Earth.

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SUSTAINABLE WATER MANAGEMENT: SCIENCE, POLICY, AND PRACTICE

R. Priyadharshini
Sri Manakula Vinayagar Nursing College,
Kalitheerthalkuppam, Puducherry 605107
Corresponding author E-mail: priyadharashinir@smvnc.ac.in

Introduction:

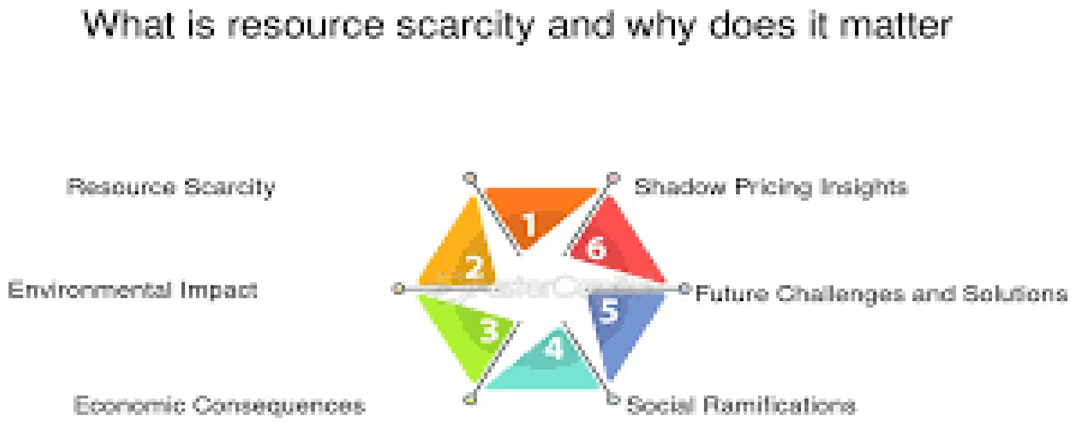
Definition

Sustainable water management (SWM) refers to the comprehensive approach of managing water resources in a way that meets current societal and environmental needs without compromising the ability of future generations to meet their own needs. It involves the integration of social, economic, and ecological considerations in the planning, development, and management of water resources. Key components include:

- **Efficiency**: Maximizing the use of available water resources to reduce waste and ensure equitable access.
- **Quality**: Protecting and improving water quality to safeguard human health and ecosystems.
- **Resilience**: Enhancing the capacity of water systems to adapt to climate change, extreme weather events, and other pressures.

Importance

1. **Resource Scarcity**: With over 2 billion people living in water-stressed areas, sustainable management is crucial to ensure access to clean water for all.



2. **Ecosystem Health**: Water is essential for maintaining healthy ecosystems. Sustainable management helps protect biodiversity and ecosystem services, such as water filtration and habitat provision.

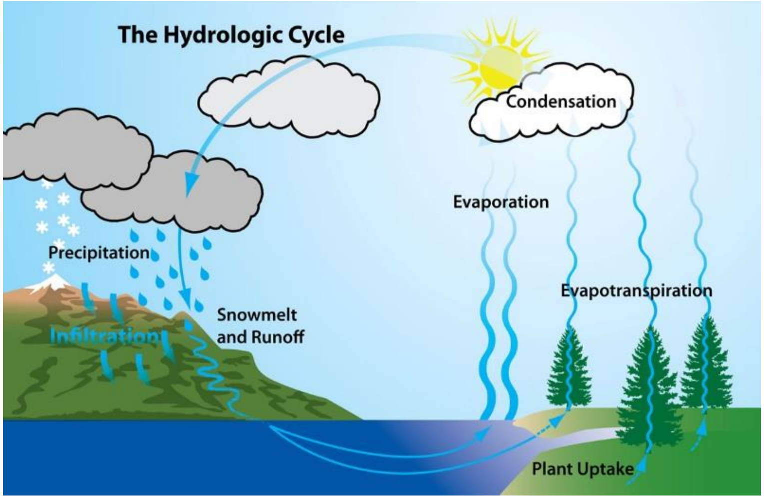
3. **Climate Change Adaptation**: As climate change alters precipitation patterns and increases the frequency of extreme weather events, SWM practices enhance resilience, ensuring that communities can adapt to these changes

4. **Economic Development**: Water is vital for agriculture, industry, and energy production. Sustainable water management supports economic growth while ensuring that water resources are used responsibly.
5. **Social Equity**: SWM promotes fair access to water resources, addressing inequalities that often leave marginalized communities without adequate water supply or sanitation.
6. **Regulatory Compliance**: Effective water management helps meet legal and regulatory requirements, reducing risks associated with water pollution and over-extraction.

- Overview of the interconnections between science, policy, and practice
- Goals of the chapter

2. Scientific Foundations of Sustainable Water Management

- **2.1 The Hydrological Cycle**



Components and Processes

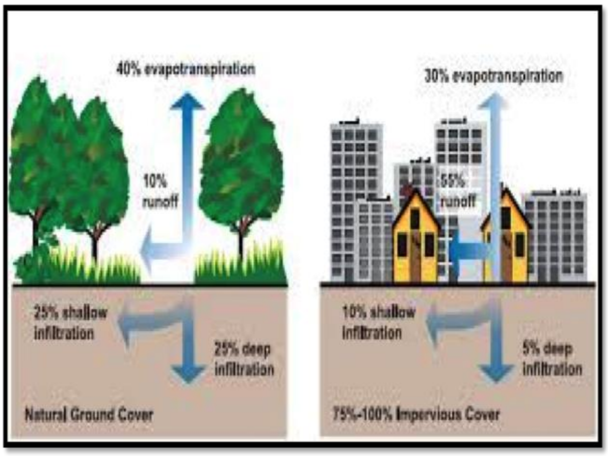
1. **Precipitation**
    - **Definition**: Precipitation is any form of water, liquid or solid, that falls from the atmosphere to the Earth's surface. This includes rain, snow, sleet, and hail.

   - **Role**: It is the primary mechanism for delivering freshwater to the Earth's surface, replenishing rivers, lakes, and groundwater.
2. **Evaporation**
   - **Definition**: Evaporation is the process by which water changes from a liquid state to a gaseous state (water vapor) due to heat from the sun.
   - **Role**: It plays a critical role in moving water from the surface (oceans, lakes, and rivers) into the atmosphere, contributing to cloud formation.
3. **Infiltration**
   - **Definition**: Infiltration is the process through which water on the ground surface enters the soil.
   - **Role**: It replenishes groundwater supplies and supports soil moisture, which is vital for plant growth.
4. **Runoff**
   - **Definition**: Runoff is the portion of precipitation that flows over the ground surface and returns to water bodies, such as rivers, lakes, and oceans.
   - **Role**: It is essential for maintaining surface water levels and transporting nutrients and pollutants.

Human Impacts on the Hydrological Cycle

1. **Urbanization**
   - **Effect**: Increased impervious surfaces (e.g., roads, buildings) lead to higher runoff and reduced infiltration, causing flooding and reduced groundwater recharge.
   - **Result**: Altered drainage patterns and increased pollution of water bodies.
2. **Agricultural Practices**
   - **Effect**: Intensive farming can lead to soil compaction and erosion, which disrupt infiltration rates and contribute to runoff.
   - **Result**: Nutrient runoff can lead to eutrophication in water bodies, harming aquatic ecosystems.
3. **Deforestation**
   - **Effect**: Removing trees decreases transpiration (the release of water vapor from plants) and alters local precipitation patterns.
   - **Result**: Increased runoff and reduced groundwater recharge can lead to dryer conditions and altered microclimates.
4. **Climate Change**
   - **Effect**: Changes in temperature and precipitation patterns affect the hydrological cycle, leading to more intense storms, altered runoff patterns, and changes in evaporation rates.

- **Result**: Increased frequency and severity of floods and droughts can stress water resources and ecosystems.



5. **Water Extraction**
    - **Effect**: Over-extraction of groundwater for agriculture, industry, and domestic use can lead to aquifer depletion.
    - **Result**: Reduced water availability and increased salinity in some regions, impacting both human use and ecological balance.
6. **Pollution**
    - **Effect**: Contaminants from industrial, agricultural, and urban sources can enter water bodies through runoff and infiltration.
    - **Result**: Deterioration of water quality, impacting drinking water supplies and aquatic life.

2.2 Water Quality and Ecosystem Health

Water Quality and Ecosystem Health

Key Indicators of Water Quality

1. **Physical Indicators**
    - **Temperature**: Affects oxygen solubility and metabolic rates of aquatic organisms.
    - **Turbidity**: Measures water clarity; high turbidity can hinder photosynthesis and disrupt aquatic habitats.
2. **Chemical Indicators**
    - **pH**: Indicates acidity or alkalinity; extreme pH levels can harm aquatic life.
    - **Dissolved Oxygen (DO)**: Essential for the survival of fish and other aquatic organisms; low levels can lead to hypoxia.
    - **Nutrients (Nitrogen and Phosphorus)**: Essential for growth but can cause eutrophication when present in excess.
3. **Biological Indicators**
    - **Biodiversity**: A diverse array of species generally indicates a healthy ecosystem.

  - **Indicator Species**: Certain species (e.g., macroinvertebrates) are sensitive to pollution and can provide insights into ecosystem health.

Impacts of Pollutants on Aquatic Ecosystems

1. **Nutrient Pollution**
   - **Eutrophication**: Excessive nutrients, particularly nitrogen and phosphorus, can lead to algal blooms that deplete oxygen levels when decomposed, resulting in dead zones where aquatic life cannot survive.
2. **Toxic Contaminants**
   - **Heavy Metals**: Substances like mercury and lead can accumulate in the food chain, causing toxicity in fish and wildlife, and posing health risks to humans.
   - **Pesticides and Pharmaceuticals**: Runoff can introduce harmful chemicals that disrupt endocrine systems in aquatic organisms.
3. **Microbial Pollution**
   - **Pathogens**: Bacteria and viruses from sewage and runoff can lead to outbreaks of disease in aquatic life and pose health risks to humans through contaminated water sources.
4. **Sedimentation**
   - **Effects on Habitat**: Increased sediment from erosion can smother habitats such as coral reefs and riverbeds, reducing biodiversity and disrupting reproductive cycles of aquatic species.

Monitoring and Assessment Techniques

1. **Field Sampling**
   - **Water Sampling**: Collecting water samples at various depths and locations to test for physical, chemical, and biological indicators.
   - **Biological Surveys**: Assessing the presence and abundance of indicator species and other aquatic organisms.

2. **Remote Sensing**
    - **Satellite Imagery**: Used to monitor large-scale changes in water bodies, such as algal blooms and temperature variations.
    - **Aerial Surveys**: Useful for assessing land-use changes and their impacts on nearby water quality.
3. **Laboratory Analysis**
    - **Chemical Testing**: Analyzing water samples for contaminants, nutrients, and dissolved oxygen levels using standardized laboratory methods.
    - **Toxicity Testing**: Assessing the effects of pollutants on specific aquatic organisms under controlled conditions.
4. **Continuous Monitoring**
    - **In-Situ Sensors**: Deploying sensors in water bodies to provide real-time data on parameters such as temperature, pH, and dissolved oxygen.
    - **Automated Sampling Stations**: Allowing for long-term monitoring and immediate detection of changes in water quality.
5. **Modeling and Data Analysis**
    - **Hydrological Models**: Used to simulate water flow and quality under various scenarios to predict the impacts of land-use changes, climate change, and pollution sources.
    - **Statistical Analysis**: Analyzing collected data to identify trends, assess compliance with water quality standards, and inform management decisions.

2.3 Climate Change and Water Resources

Effects of Climate Variability on Water Availability

1. **Altered Precipitation Patterns**
    - **Increased Intensity**: Climate change can lead to more intense and sporadic rainfall events, resulting in flooding and reduced groundwater recharge.
    - **Droughts**: Regions may experience prolonged dry spells, reducing surface water and groundwater availability, impacting agriculture and drinking water supplies.
2. **Melting Glaciers and Snowpack Decline**
    - **Reduced Snowmelt**: Many regions depend on snowmelt for water supply. Warmer temperatures can lead to earlier snowmelt, disrupting seasonal water availability.
    - **Glacial Retreat**: As glaciers shrink, initially, water flow may increase, but over time, this will diminish, threatening water supply for communities relying on glacial runoff.

3. **Increased Evapotranspiration**
    - **Higher Temperatures**: Warmer temperatures can increase evaporation from soil and water bodies, reducing overall water availability.
    - **Soil Moisture Loss**: Increased evapotranspiration can lead to drier soils, affecting agriculture and natural ecosystems.
4. **Rising Sea Levels**
    - **Saltwater Intrusion**: Coastal aquifers are at risk from rising sea levels, leading to saltwater intrusion that contaminates freshwater supplies, particularly in low-lying areas.
5. **Extreme Weather Events**
    - **Increased Frequency and Severity**: More frequent and severe storms can lead to flash flooding, while other regions may suffer from increased droughts, creating uneven distribution of water resources.

Adaptation Strategies for Managing Water Resources

1. **Integrated Water Resources Management (IWRM)**
    - **Holistic Approach**: Encourages the coordinated management of water, land, and related resources to optimize social, economic, and environmental outcomes.
    - **Stakeholder Engagement**: Involves local communities, governments, and businesses in decision-making processes to ensure that diverse needs are met.
2. **Water Conservation Practices**
    - **Efficiency Improvements**: Implementing technologies and practices that reduce water waste in agriculture, industry, and urban settings (e.g., drip irrigation, rainwater harvesting).
    - **Public Awareness Campaigns**: Educating communities about the importance of water conservation and how to implement water-saving practices.
3. **Enhancing Water Storage and Infrastructure**
    - **Reservoir Construction**: Building or upgrading reservoirs to capture and store excess runoff during heavy rainfall.
    - **Aquifer Recharge**: Promoting practices that enhance groundwater recharge, such as creating recharge basins and restoring wetlands.
4. **Ecosystem-Based Approaches**
    - **Restoration of Natural Landscapes**: Protecting and restoring wetlands, forests, and watersheds to enhance natural water filtration and storage capabilities.
    - **Biodiversity Protection**: Maintaining healthy ecosystems that provide resilience against climate impacts.

5. **Climate-Resilient Agricultural Practices**
    - **Crop Diversification**: Introducing drought-resistant and climate-adapted crops to ensure food security under changing conditions.
    - **Soil Management**: Implementing practices such as cover cropping and no-till farming to improve soil moisture retention.
6. **Policy and Governance Enhancements**
    - **Flexible Water Management Policies**: Adapting policies to be responsive to changing climate conditions and emerging water availability issues.
    - **Investment in Research and Technology**: Supporting the development of new technologies and practices that enhance water resource management and climate adaptation.
7. **Community-Based Adaptation Initiatives**
    - **Local Knowledge Integration**: Leveraging traditional ecological knowledge and local practices to inform adaptive management strategies.
    - **Capacity Building**: Empowering communities with the knowledge and tools needed to adapt to climate change impacts on water resources.

Practical Approaches to Sustainable Water Management

Water Conservation Strategies

Techniques for Domestic, Agricultural, and Industrial Water Conservation

1. **Domestic Water Conservation**
    - **Low-Flow Fixtures**: Installing low-flow toilets, showerheads, and faucets to reduce water usage in households.
    - **Rainwater Harvesting**: Collecting rainwater from roofs and directing it to storage systems for irrigation and non-potable uses.
    - **Smart Irrigation Systems**: Utilizing drip irrigation and soil moisture sensors to optimize watering schedules and minimize waste.
    - **Water-Saving Appliances**: Using water-efficient dishwashers and washing machines to reduce consumption while maintaining performance.

   - **Public Education Campaigns**: Raising awareness about the importance of water conservation and encouraging practices like shorter showers and turning off taps while brushing teeth.
2. **Agricultural Water Conservation**
   - **Drip Irrigation**: Implementing drip irrigation systems that deliver water directly to plant roots, reducing evaporation and runoff.
   - **Soil Moisture Management**: Using techniques like mulching and cover cropping to retain soil moisture and enhance water infiltration.
   - **Crop Selection and Rotation**: Choosing drought-resistant crops and implementing crop rotation to improve resilience and reduce water demand.
   - **Rainfed Agriculture**: Designing farming practices that maximize the use of natural rainfall, reducing reliance on irrigation.
   - **Precision Agriculture**: Utilizing technology to monitor soil moisture and weather patterns, allowing for targeted water application.
3. **Industrial Water Conservation**
   - **Water Recycling and Reuse**: Implementing systems to treat and reuse wastewater within industrial processes, reducing overall demand.
   - **Process Optimization**: Analyzing and improving manufacturing processes to minimize water use and prevent waste.
   - **Cooling System Innovations**: Using closed-loop cooling systems or evaporative cooling technologies to reduce water consumption in industrial applications.
   - **Employee Training**: Educating employees about water conservation practices and encouraging a culture of efficiency in the workplace.

Role of Technology in Enhancing Water Efficiency

1. **Smart Water Management Systems**
   - **Sensors and IoT**: Deploying Internet of Things (IoT) devices and sensors to monitor water usage in real time, enabling data-driven decision-making.
   - **Automated Control Systems**: Using smart controllers for irrigation systems that adjust water application based on weather forecasts and soil moisture levels.
2. **Remote Sensing and Drones**
   - **Satellite Imaging**: Utilizing satellite data to assess large-scale water use and identify areas needing attention, such as over-irrigated fields.
   - **Drones**: Employing drones equipped with thermal imaging to monitor crop health and water stress, allowing for targeted irrigation.

3. **Water Quality Monitoring Technologies**
    - **Real-Time Monitoring**: Implementing sensors to continuously monitor water quality, helping to detect contamination and ensure safe water supplies.
    - **Data Analytics**: Using big data analytics to process water usage patterns and predict future demands, enabling better resource allocation.
4. **Desalination Technologies**
    - **Innovative Desalination Methods**: Advancements in desalination technology, such as reverse osmosis, can provide fresh water from seawater, particularly in arid regions.
5. **Cloud-Based Management Systems**
    - **Water Management Software**: Cloud-based platforms allow for the integration of data from various sources, facilitating better planning, distribution, and monitoring of water resources.
6. **Public Engagement Platforms**
    - **Mobile Apps**: Developing apps that provide users with information on water conservation practices and enable them to track their water usage.

Summary

This chapter has explored the multifaceted nature of sustainable water management (SWM) by examining its scientific foundations, policy frameworks, and practical approaches. Key topics covered include:

1. **Scientific Foundations**: Understanding the hydrological cycle and its components—precipitation, evaporation, infiltration, and runoff—has highlighted how human activities impact water availability and quality. Climate change further complicates these dynamics, leading to altered precipitation patterns and increased evaporation.
2. **Water Quality and Ecosystem Health**: We discussed critical indicators of water quality, such as temperature, dissolved oxygen, and nutrient levels. The chapter also examined the impacts of pollutants on aquatic ecosystems and outlined various monitoring and assessment techniques essential for maintaining water quality.
3. **Policy Frameworks**: Integrated Water Resources Management (IWRM) has been emphasized as a holistic approach that promotes collaboration among stakeholders. We also highlighted the importance of regulatory measures, international cooperation, and adaptive governance in addressing water management challenges.
4. **Practical Approaches**: Effective water conservation strategies across domestic, agricultural, and industrial sectors were detailed. The role of technology in enhancing water efficiency—through smart management systems, remote sensing, and innovative practices—was underscored as essential for sustainable water use.

Conclusion:

Sustainable water management is a critical component of achieving environmental sustainability, economic resilience, and social equity. The interconnections between science, policy, and practice demonstrate that a multidisciplinary approach is necessary for effective water resource management.

As we face growing challenges such as climate change, population growth, and increasing water demand, it is imperative to implement adaptive strategies that prioritize water conservation and efficiency. Engaging communities, leveraging technology, and fostering collaboration among stakeholders will be essential to ensure a resilient water future.

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PESTICIDES AND THEIR ENVIRONMENTAL IMPACTS

Meenakshi

Department of Chemistry,

University of Rajasthan, Jaipur, Rajasthan, India.

Corresponding author E-mail: meenakshialwaraj@gmail.com

Abstract:

Chemical substances known as pesticides are used to eradicate various pests, such as weeds, fungus, insects, and rodents. Worldwide, about a thousand different pesticides are in use. In order to fulfill consumer demand for food, pesticide technologies have continued to produce a broad variety of pesticides. Although these pesticides are hazardous to the environment, they are regarded as an essential tool for crop development and protection. Overuse of pesticides can result in the devastation and loss of biodiversity. In our world, biodiversity is essential to human survival. Numerous species, including birds, aquatic life, and mammals, are harmed by pesticides. One of the main causes of concern for the planet's long-term sustainability is pesticides. This chapter will cover the pesticides, their types, and how they affect the environment. In addition, pesticide pollution and the long-term effects of pesticides on the environment are also covered in this chapter.

Introduction:

Natural or artificial substances intended to eradicate all kinds of pests are known as pesticides. Pesticides are chemicals used to control pests or stop them from growing. Pesticides are used to get control of weeds, fungus, rodents, and insects. These comprise a variety of substances, such as plant growth regulators, molluscicides, rodenticides, fungicides, insecticides, herbicides, nematicides, and other substances. It is often used to stop illnesses brought by vectors and plays significant roles in both commercial and food-based industrial activities, including agriculture, aquaculture, food processing, and storage.

The term pesticide has defined as any material or combination of materials meant to prevent, eliminate, or manage any pest, including those that spread disease to humans or animals, undesired plant or animal species, and anything that could harm or otherwise obstruct the production, processing, storage, transportation, or marketing of food, agricultural products, wood and wood products, animal feed, or materials that could be given to animals to control insects, or other pests in or on their bodies. The phrase encompasses materials designed to be used as a desiccant, defoliant, thinning fruit agent, or to avoid premature fruit fall. Additionally utilized as materials sprayed on crops either prior to or during harvest to guard against degradation of the product during transportation and storage.

Production of Pesticides in India

About 8000 crore worth of pesticides is produced annually in the nation; 6000 crores of them are used domestically and the remaining portion is exported. Roughly 60 companies in the nation manufacture technical pesticides, and about 500 units make their formulations. During the financial year 2023–2024, India produced 258 thousand metric tons of pesticides. The nation's chemical sector is quite diverse. The nations of South Asia are the world's top manufacturers of chemicals, covering thousands of products.

In India, the pesticide market is worth billions of dollars. In order to fulfill the food needs of its expanding population and improve agricultural productivity, the nation has started using more pesticides. In India, the per capita use of pesticides increased in order to raise the average agricultural output per hectare. The number of pesticides produced in the nation increased at a positive yearly growth rate.

In India, Bayer Crop Science Limited was one of the major pesticide manufacturers. It began operations in 2002 and offered a broad range of products that could be used with different types of crops. Some other top players included Tata Group subsidiary Rallies India Limited along with NACL Industries Limited, UPL Limited, and Bharat Rasayan Limited. Based on market capitalization, Rallies was one of the leading companies as of 2020.

Consumption of Pesticides in India

The states of Uttar Pradesh, Maharashtra, Andhra Pradesh, Punjab, and Haryana are responsible for seventy percent of India's overall pesticide usage. Utter Pradesh is the leading consumer (Fig. 1).

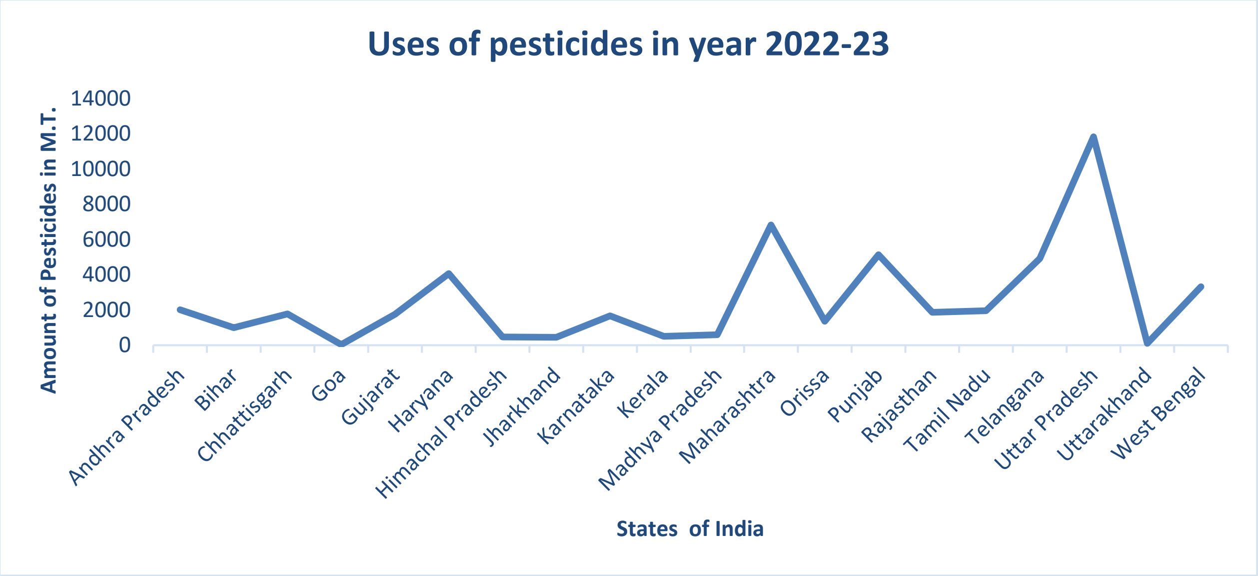

Figure 1: State -wise consumption of chemical pesticides in M.T.

Types of pesticides

Pesticides are categorized according to a number of factors. The three most often utilized factors for classifying pesticides are their mechanism of entry, chemical composition, and intended target destruction. However, the Globally Harmonized System (GHS) and the World Health Organization (WHO) categorized pesticides based on their toxicity or harmful effects since they recognized the importance of public health. In order to improve agricultural productivity and food preservation, we must apply pesticides while taking into account their danger concerns. However, its excessive usage, exposure, and harmful effects can be reduced by using it sparingly and in conjunction with other pesticide classes. Pesticides are categorized according to a number of factors, including their toxicity (dangerous consequences), the type of pest organisms they eradicate, their chemical composition, mechanism of action, channel of entrance, mode of action, manner and timing of operation, formulations, and their origins. Table 1 illustrates the pesticides types on the basis of pest organism they kill and pesticide function.

Table 1: Different types of Pesticides

Types of Pesticides	Target pests and function	Examples
Fungicides	To prevent and eradicate the fungi	Bordeaux mixture, Cymoxanil, thiabendazole,
Insecticides	To kill insects or to inhibit their growth	DDT, Azadirachtin, chlorpyrifos, malathion, etc.
Herbicides	To kill the plants, or to inhibit their growth or development.	paraquat Alachlor
Bactericides	To kill or inhibit bacteria	Streptomycin, tetracycline
Algicide	To kill or inhibit algae	Copper Sulphate, diuron, Oxyfluorfen
Rodenticides	To kill rats and related animals	Strychnine, Warfarin, zinc phosphide
Nematicides	To control nematodes	Carbofuron, chlorpyrifos, methyl bromide
Molluscicides	To kill slugs and snails	Metaldehyde, thiadicarb
Acaricides	To kill mites and ticks or to disrupt their growth or development	DDT, dicofol, chlorpyrifos, Permethrin
Larvicides	Inhibit the growth of larvae.	Methoprene
Avicides	To kill birds	Strychnine, Fenthion
Termiticides	Kill termites	Fipronil
Ovicides	Inhibit the growth of eggs of insects and mites	Benzoxazin

Benefits of Pesticides

Pesticides have three main effects:

- They control agricultural pests (diseases, weeds, and plant disease vectors).
- They control disease vectors that affect humans and livestock.

- They prevent or control organisms that damage other human activities and structures.

The overall benefits are can be categories in primary and secondary benefits.

***Primary benefits**:* The direct gains expected from their use are included in primary benefits. These are shown in Table 2.

Table 2: Primary benefits of Pesticides

PRIMARY BENEFITS		
Managing pests and the carriers of plant diseases	Managing noxious organisms and disease-carrying agents for humans and cattle	Stop or manage creatures that endanger other human endeavors and infrastructure
• Reduced fungal toxins • Improved shell life of produce • Improved crop/livestock quality • Improved crop/livestock yields • Retailer networks established • Invasive species controlled • Reduced soil disturbance • Vector disease control • Reduced drudgery of weeding	• Animals saved • Animal suffering reduced • Human lives saved • Human suffering reduced • Human disturbance reduced • Increased livestock quality • Increased livestock yields	• Root/moisture damage prevented • Recreational turf protected • Garden plants protected • Drivers view unobstructed • Tree/bush/leaf hazards prevented • Civic ornamentals protected • Masonry/paint/plastics/fuel etc. protected • Wooden structures protected

***Secondary benefits**:* The less evident or immediate advantages that follow from the main advantages are known as the secondary benefits. They might be more long-term, subtle, or less immediately apparent. Because of this, it is more difficult to prove cause and effect for secondary advantages, although they can still be strong arguments in favor of using pesticides. These are the longer-term, less apparent, or less immediate effects. Consequently, secondary advantages might be strong arguments for the use of pesticides even if it is more difficult to prove cause and effect. Table 3 represents the secondary benefits of the use of pesticides.

Table 3: Secondary benefits of Pesticides

SECONDARY BENEFITS		
COMMUNITY BENEFITS	NATIONAL BENEFITS	GLOBAL BENEFITS
• Food safety • Food security • Quality of life improved	• Workforce productivity increased • Agronomic advice improves cropping	• Habitable areas increase • Biodiversity conserved

• Farm and agribusiness revenues • Labor freed for other tasks • Life expectancy increased • Nutrition and health improved • Wider range of viable crops • Reduced vet and medical costs • Fitter populations • Reduced stress • Reduced maintenance costs	• National agricultural economy increases • Increased export revenues • Reduced soil erosion/ moisture loss • Fewer transport accidents • Migration to cities reduced • Pleasant urban area	• Assured safe and diverse food supply • International tourism revenue • Less pressure on uncropped land • Less green house gas • Fewer pest introductions elsewhere • Less international disease spread • Timber is viable in construction • Shade tree reduce global warming

Hazards of Pesticides

Pesticides have ability to contaminate every part of the environment. Pesticides can be hazardous to human health and the environment in many ways. Some of them are listed below:

- ***Air pollution:*** Pesticides can enter surrounding regions through volatilization or wind-borne particles. A few things that influence the dispersal of pesticides in the air include the temperature, relative humidity, and weather at the time of application. Compared to aerial spraying, ground spraying results in less spread.
- ***Water pollution:*** Pesticides enter the water system primarily through three channels: Sprays have the potential to percolate, or leach, into the soil and be taken up by runoff from the water. Following water contamination, a number of issues arise, including the extinction of aquatic life, deterioration of drinking water quality, reduction in agricultural water availability, and modification of the physical features of water bodies. Generally, insecticides are more hazardous to aquatic life than fungicides and herbicides. In aquatic bodies, pesticides can build up and harm fish-eating insects and zooplankton. Fish, plants, invertebrates, bacteria, and other elements of the aquatic environment can suffer from pesticide use.
- ***Soil Pollution:*** Pesticides are source of soil contamination, they affect soil micro-organisms, decreases soil fertility, and affect plant growth.
- ***Effects of pesticides on plants****:* They have a negative impact on the fixation of nitrogen. Pesticides have the ability to kill bees and reduce pollinators, which has an impact on crop pollination.
- ***Effects of pesticides on animals****:* Some animal's primary food sources may be destroyed by pesticides. Earthworms break down organic materials and enrich the uppermost layer

of soil with nutrients. Pesticides negatively impact earthworm development and reproduction. Exposure to pesticides has been connected in a number of species to developmental abnormalities, cancer, liver damage, and birth problems.

- ***Health effects**:* Pesticides exposure can cause a range of health effects. Acute effects (short term effects: rashes, nausea, dizziness, stinging eyes etc.), carcinogenic effects (through repeated exposure of pesticides), chronic effects (long term effect: birth defects, cancer, neurological disorders, reproductive harm), and endocrine disruption are some major health effects.
- ***Biodiversity reduction**:* Pesticides can reduce biodiversity, reduce Nitrogen fixation, and contribute to pollinator decline. Pesticides can threaten endangered species.
- ***Environmental effects**:* Pesticides can harm the environment in many ways, including biodiversity loss, pollinator harm, and disturbing eco cycles of the environment.
- ***Bioaccumulation:*** It is the process by which pesticide-contaminated food builds up in the body until it reaches a dangerous level in a person who regularly consumes it.
- ***Biomagnification**:* Excessive use of pesticides results its high concentration in the food chain.
- ***Impact on microorganisms**:* Pesticides can disrupt essential microorganisms including bacteria, fungus, algae, and plankton's respiration, growth rate, reproduction, and photosynthetic processes.
- ***Development of pesticide resistance:*** Long-term pesticide usage can cause some pests to acquire pesticide resistance. The emergence of resistance makes pest management more challenging.

How to Reduce Pesticide Pollution

Pesticides are now a main part of today’s life. We cannot stop using pesticides, but by following some methods and precautions we can minimize the pesticide pollution. Some of them are included below:

- Use integrated pest management system.
- Use of biological control such as pheromone and microbial pesticides.
- Use genetic engineering and techniques to tamper with insect reproduction.
- Use polyculture and crop rotation techniques.
- Biological pesticides based on entomopathogenic fungi, bacteria, or viruses that cause disease in the pest species can also be utilized.
- Natural predators or parasites of the pests can be employed.

Conclusions:

The application of pesticides has greatly benefited a number of industries, including public health and agriculture. But excessive use of pesticides adversely affect environment in many ways. Therefore, it is necessary to limit pesticide contamination and its negative impacts on the ecosystem and other non-target organisms. Inappropriate pesticide usage, management, and behavior in the environment lead to pollution in the form of polluted food, water, soil, and air. More study on environmental and occupational exposures, as well as the health concerns connected to pesticide use, is needed to advance our knowledge of pesticide use and management in the future. New scientific approaches and technologies should be used in conjunction with feasible initiatives like integrated pest management (IPM), legislation banning high-risk pesticides, and the development of national implementation plans (NIPs) to lessen the harmful effects of pesticide contamination on non-target organisms and the environment. Biopesticides should be developed in conjunction with chemical pesticides to lower the danger of pesticide contamination. It is also essential to communicate the scientific findings of exposure and occupational and environmental health risk assessments in order to provide scientific training for pesticide application, prevent harmful health effects from pesticide usage, and promote safety for applicators and communities in support of sustainable development.

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CLIMATE CHANGE, MICROPLASTICS AND CYANOBACTERIAL BLOOM: A TRIFECTA OF WETLAND STRESSORS

Arun T. Ram*[1] and P Tessy Paul[2]

[1]PG & Research Department of Botany,
St. Peter's College, Kolenchery, Ernakulam District, Kerala – 682 311
(Affiliated to Mahatma Gandhi University, Kottayam, Kerala, India)
[2]Department of Botany,
Christ College (Autonomous), Irinjalakuda, Thrissur District, Kerala- 680 125
(Affiliated to University of Calicut, Malappuram, Kerala, India)
*Corresponding author E-mail: aruntram@gmail.com

Abstract:

Wetland ecosystems face unprecedented challenges from a combination of anthropogenic stressors. Primarily, the interactions and cumulative impacts of three major environmental stressors on wetland ecosystems such as climate change, microplastic pollution, and cyanobacterial bloom are discussed. It also examines how climate change is exacerbating the effects of microplastic pollution and promoting the proliferation of harmful cyanobacterial blooms and the role of microplastics in the potential spread and toxicity of these blooms. The synergistic effects of these stressors are analysed, revealing complex feedback loops that amplify their impacts on wetland biodiversity, water quality, and ecosystem services. Emerging technologies and integrative approaches show promise in monitoring and mitigating these combined threats. Understanding these complex dynamics is crucial for developing effective management strategies to protect and restore wetland ecosystems in the face of these escalating threats.

Keywords: Climate Change Impacts, Microplastic Pollution, Cyanobacterial Bloom, Environmental Pollution, Wetland Degradation

Introduction:

Wetlands are among the most productive ecosystems on earth and face unprecedented challenges in the 21st century. These valuable habitats are threatened by interrelated stressors such as climate change, microplastic pollution, and cyanobacterial blooms (Ramsar Convention on Wetlands, 2018). Climate change alters the hydrology, biogeochemistry, and species composition of wetlands (Erwin, 2009; Junk *et al.*, 2013). Microplastics, ubiquitous pollutants in these ecosystems, threaten biota and interact with other pollutants (He *et al.*, 2020; Horton *et al.*, 2017). Algal or cyanobacterial blooms, triggered by nutrient enrichment and warming waters, produce toxins, deplete oxygen, and alter food webs (Huisman *et al.*, 2018; Paerl & Otten, 2013). The synergistic interactions among these stressors create a 'perfect storm' scenario that potentially pushes wetlands towards tipping points (Green *et al.*, 2017). Understanding their individual and combined impacts is crucial for developing effective management strategies and ensuring wetland ecosystem resilience in the face of global environmental change.

Wetlands cover approximately 6% of the global land surface (Davidson *et al.,* 2018) and include diverse habitats such as marshes, swamps, peatlands, and mangroves. These ecosystems provide crucial services for human well-being and environmental sustainability. Wetlands purify water by removing pollutants and excess nutrients (Verhoeven *et al.,* 2006), store significant amounts of carbon (Mitsch *et al.,* 2013), and support rich biodiversity, including rare and endangered species (Keddy, 2010). Economically, they contribute to flood control, coastal stabilization, groundwater recharge, and support livelihoods through fisheries, agriculture, and tourism (Ramsar Convention on Wetlands, 2018). Despite their immense value, wetlands are among the most threatened ecosystems globally. Since 1970, over 35% has been lost due to human activities and environmental changes (Davidson, 2014). This loss highlights the urgent need for conservation and restoration efforts to preserve these vital ecosystems and their invaluable services.

Climate change impacts mangroves through sea-level rise, altered precipitation, and increased temperatures, potentially leading to habitat loss and reduced carbon sequestration (Ward *et al.,* 2016). Microplastics accumulate in mangrove sediments, affecting soil properties and potentially impacting root systems and fauna (Nor & Obbard, 2014). These particles can also transport contaminants, degrading water and soil quality (Li *et al.,* 2018). Although less common in mangroves, changes caused by climate change can potentially increase cyanobacteria blooms, leading to hypoxia and toxin production, and affecting mangrove health and biodiversity (Paerl & Paul, 2012; Ram, 2022). The interaction of these stressors creates synergistic effects that intensify their effects. Hydrological changes caused by climate change can concentrate pollutants and create favourable conditions for cyanobacterial growth (Gomes *et al.,* 2019). This complex interaction requires integrated management approaches to maintain important mangrove ecosystem services such as coastal protection, carbon storage, and habitat provision (Alongi, 2015).

This comprehensive overview of the individual and combined impacts of climate change, microplastic pollution, and cyanobacterial blooms on wetland ecosystems. The objectives are to: (1) examine how each stressor affects wetland structure and function; (2) explore potential synergistic interactions; (3) assess cascading effects on biodiversity, biogeochemical cycles, and ecosystem services; and (4) discuss challenges in research, monitoring, and managing these diverse stressors. The scope encompasses coastal, inland, and high-latitude wetlands for a global perspective. By synthesizing current knowledge and identifying key gaps, it aims to inform future research directions and management strategies for enhancing wetland resilience and also to contribute to the development of integrated approaches for wetland conservation and restoration in an era of rapid global change.

Understanding the Concepts of Stressors

In the context of wetland ecosystems, stressors are external factors that disrupt the natural functioning and structure of these environments, potentially leading to degradation or loss of ecosystem services (Breitburg *et al.,* 2015). The concept of ecological stress is based on the recognition that ecosystems have certain abilities to withstand disturbances, but when this ability is exceeded, significant alterations in ecosystem structure and function can occur (Rapport *et al.,* 1985). In recent decades, the increasing anthropogenic pressures on wetlands have introduced novel stressors and intensified existing ones, creating complex scenarios of multiple, interacting stressors (Ormerod *et al.,* 2010; Ram & Paul, 2024). Climate change, microplastic pollution, and cyanobacterial bloom are stressors that pose multiple challenges to wetland ecosystems. In order to understand these stressors, their temporal and spatial dimensions, their intensity and their mechanisms of action must be taken into account.

Climate Change: Transforming Wetland Ecosystems Globally

Climate change is fundamentally altering wetland ecosystems worldwide, impacting their structure, function, and biodiversity. Rising temperatures and shifting precipitation patterns are causing significant changes in wetland hydrology, which is the primary driver of wetland ecosystem processes (Erwin, 2009). These changes can lead to alterations in water levels, hydroperiods, and water chemistry, ultimately affecting the composition and distribution of wetland flora and fauna. The Intergovernmental Panel on Climate Change (IPCC) has highlighted that wetlands are particularly vulnerable to climate change impacts due to their sensitivity to water balance and temperature changes (IPCC, 2014).

One of the most notable impacts of climate change on wetlands is sea level rise, which poses a particular threat to coastal wetlands. As sea levels increase, saltwater intrusion into freshwater wetlands can occur, leading to shifts in vegetation communities and potential loss of wetland area (Kirwan & Megonigal, 2013). Some wetlands may be able to migrate inland in response to rising sea levels, but this is often hindered by human infrastructure and topography, resulting in a phenomenon known as “coastal squeeze” (Pontee, 2013). Climate change is altering the carbon dynamics of wetland ecosystems. Wetlands are significant carbon sinks, storing large amounts of carbon in their soils and vegetation. However, warmer temperatures can accelerate decomposition rates and potentially turn wetlands from carbon sinks into carbon sources (Mitsch *et al.,* 2013). This shift could create a positive feedback loop, further exacerbating climate change impacts. The frequency and intensity of extreme weather events, such as droughts and floods, are expected to increase due to climate change. These events can have profound effects on wetland ecosystems, altering their hydrological regimes and potentially leading to long-term changes in ecosystem structure and function (Junk *et al.*, 2013). Prolonged droughts can cause wetland desiccation, while increased flooding can lead to erosion and sedimentation issues.

Climate change also drives shifts in species composition and biodiversity within wetland ecosystems. Changes in temperature and hydrology can alter the phenology, affecting species interactions and ecosystem functions (Visser & Both, 2005). Changes in the timing of insect emergence may not align with the breeding seasons of wetland-dependent birds, affecting their reproductive success. Understanding and predicting these climate-driven transformations is crucial for developing effective wetland conservation and management strategies. This requires interdisciplinary research approaches that integrate climate modelling with ecological studies to project future scenarios and inform adaptive management practices (Junk *et al.,* 2013). Climate change facilitates the spread of invasive species in wetland ecosystems. Altered environmental conditions can create opportunities for non-native species to establish and outcompete native flora and fauna, potentially leading to significant changes in ecosystem composition and functioning (Rahel & Olden, 2008). This can have cascading effects throughout the food web and alter ecosystem services provided by wetlands.

The cascading effects of these climate-induced changes can significantly impact the wetland ecosystem services. Changes in hydrological regimes can affect a wetland’s capacity to mitigate flooding and water purification (Moomaw *et al.,* 2018). Changes in vegetation composition may influence a wetland’s ability to sequester carbon or provide habitat for wildlife. The complex interactions between climate change and other stressors, such as pollution and land-use changes, can create synergistic effects that amplify the overall impact on wetland ecosystems (Green *et al.,* 2017). As climate change continues to reshape wetland ecosystems globally, our ability to mitigate its impacts and enhance wetland resilience will be critical for preserving these valuable habitats and their essential ecosystem services.

Microplastics: The pervasive pollutant in wetland ecosystems

Microplastics, defined as plastic particles less than 5 mm in size, have emerged as a ubiquitous and persistent pollutant in aquatic ecosystems including wetlands. These tiny plastic fragments originate from various sources, including the decomposition of larger plastic debris, industrial processes, and consumer products such as cosmetics and synthetic textiles (Rochman *et al.,* 2019). The pervasive nature of microplastics in wetland environments poses significant challenges to ecosystem health and functioning.

Wetlands which act as natural sinks for sediments and pollutants, are particularly vulnerable to microplastic accumulation. Recent studies have shown that wetlands can trap and retain microplastics, with concentrations often higher than in surrounding aquatic environments (He *et al.,* 2020). This accumulation is facilitated by the complex hydrology and vegetation structure of wetlands, which can slow water flow and enhance particle deposition. The presence of microplastics in wetland ecosystems can have far-reaching consequences for flora and fauna. Aquatic organisms, from zooplankton to fish, can ingest microplastics, mistaking them for food particles. This ingestion can cause physical harm, such as intestinal constipation and reduced ability to absorb food as well as potential toxicological effects from associated contaminants (Wright *et al.,* 2013).

Microplastics can serve as vectors for other pollutants, potentially exacerbating their impact on wetland ecosystems. Plastic particles can adsorb and concentrate various pollutants, including persistent organic pollutants (POPs) and heavy metals, from the surrounding water (Teuten *et al.,* 2009). When ingested by organisms, these contaminated microplastics can lead to biomagnification of toxins in the food web, potentially affecting even top predators and posing risks to human health through the consumption of contaminated fish and shellfish (Barboza *et al.*, 2018). The interaction between microplastics and wetland vegetation is of increasing concern. Recent research suggests that microplastics can affect plant growth and physiology. A study by Rillig *et al.* (2019) found that microplastics in soil can alter plant biomass and root traits. In wetlands, where plants play crucial roles in ecosystem function, such effects could have cascading effects on habitat structure, nutrient cycling, and carbon sequestration. Microplastics can influence biogeochemical cycles in wetlands. The presence of plastic particles can alter microbial communities and their activities, potentially affecting crucial processes such as nitrogen fixation and methane production (Seeley *et al.,* 2020). These changes could impact wetland carbon dynamics and greenhouse gas emissions, linking microplastic pollution to broader impacts of climate change.

The longevity of microplastics in the environment makes their impact on wetland ecosystems even more complex. Unlike many organic pollutants, microplastics do not readily biodegrade and can persist in wetland sediments for extended periods, potentially serving as a long-term source of contamination (Barnes *et al.*, 2009). This persistence means that even if plastic inputs were stopped immediately, the effects of microplastic pollution in wetlands would likely last for decades. Solving the problem of microplastic pollution in wetlands requires a multifaceted approach. This includes reducing plastic waste at the source, improving waste management systems, and developing more effective methods for removing microplastics from aquatic environments. Further research is needed to fully understand the long-term ecological impacts of microplastics on wetland ecosystems and to develop strategies for mitigating these effects (Peng *et al.,* 2020).

Cyanobacterial Bloom: Symptoms of Ecosystem Imbalance in Wetlands

Eutrophication is the excessive enrichment of water bodies with nutrients, primarily nitrogen and phosphorus. In wetlands, this process often results from agricultural runoff, urban wastewater, and atmospheric deposition. The influx of nutrients stimulates rapid growth of algae, cyanobacteria and aquatic plants, leading to significant changes in the ecosystem. Cyanobacterial blooms, characterized by the rapid proliferation of cyanobacteria (also known as blue-green algae) in aquatic ecosystems are becoming increasingly prevalent in wetlands worldwide and these cyanobacterial blooms serve as critical indicators of underlying ecosystem imbalances, often due to anthropogenic pressures and environmental changes (O'Neil *et al.,* 2012). The occurrence and intensification of cyanobacterial blooms in wetlands represent a complex interplay of various factors, including nutrient enrichment, climate change, and altered hydrological regimes.

The main causes of cyanobacterial blooms in wetlands are eutrophication, and the excessive enrichment of water bodies with nutrients, particularly nitrogen and phosphorus. Anthropogenic activities such as agricultural runoff, urban development, and inadequate wastewater treatment have significantly increased nutrient loads in many wetland ecosystems (Smith *et al.,* 1999). Cyanobacteria are particularly adept at exploiting these nutrient-rich conditions and often displace other phytoplankton species due to their ability to fix atmospheric nitrogen and store excess phosphorus (Paerl & Otten, 2013).

Climate change is increasing the frequency and intensity of cyanobacterial blooms in wetlands. Increasing temperatures favour the growth of many cyanobacterial species because they generally have higher temperature optima compared to other phytoplankton (Paerl & Huisman, 2009). Higher temperatures increase stratification in the water column, which can lead to nutrient enrichment in surface waters and create ideal conditions for bloom formation. Changes in precipitation patterns associated with climate change can also influence floral dynamics by altering wetland hydrology and nutrient influx (Moss *et al.,* 2011). The proliferation of cyanobacterial blooms can have far-reaching consequences for wetland ecosystems. Dense blooms can significantly reduce light penetration in the water column, negatively impacting submerged aquatic vegetation and altering habitat structure (Paerl & Otten, 2013). As blooms decay, hypoxic or anoxic conditions can occur resulting in fish kills and release of sediment-bound nutrients, further promoting bloom persistence (Huisman *et al.,* 2018).

Many cyanobacterial species produce a variety of toxic secondary metabolites, collectively referred to as cyanotoxins. These toxins pose significant risks to wildlife, domestic animals, and human health. Exposure to cyanotoxins can occur through direct contact, ingestion of contaminated water, or consumption of fish and shellfish that have accumulated these toxins (Carmichael & Boyer, 2016). In wetland ecosystems, cyanotoxins can accumulate in the food web, potentially affecting a wide range of organisms from zooplankton to top predators. Cyanobacterial blooms also influence biogeochemical cycles in wetlands. During this phenomenon, cyanobacteria can alter nutrient cycling processes, potentially leading to increased internal nutrient loading and creating feedback loops that maintain bloom conditions (Cottingham *et al.,* 2015). Cyanobacterial blooms can influence carbon cycling in wetlands, as they contribute to carbon sequestration through primary production and carbon release through respiration and decomposition (Visser *et al.,* 2016).

Managing and mitigating cyanobacterial blooms in wetlands has significant challenges. Traditional approaches such as nutrient reduction remain crucial but may not be sufficient in the face of climate change and other environmental stressors. Emerging strategies include biomanipulation techniques, such as the introduction of macrophytes or grazing organisms to control cyanobacterial growth, and the use of hydrogen peroxide as a selective algicide (Lürling *et al.,* 2016). However, these methods often require careful consideration of potential ecological impacts and may not be suitable for all wetland types. The increasing prevalence of cyanobacterial blooms in wetlands underscores the need for comprehensive monitoring programmes and early warning systems. Advanced techniques such as remote sensing and molecular methods are being developed and applied to improve cyanobacterial bloom detection and prediction (Koreivienė *et al.,* 2014). Combined with a better understanding of cyanobacterial bloom ecology, these tools can help inform management decisions and policy development aimed at protecting wetland ecosystems.

Synergistic Interactions among the Stressors

The synergistic interactions between climate change and microplastic pollution in wetland ecosystems represent a complex and growing concern for researchers and environmental managers. These two stressors can amplify each other's effects, potentially leading to more severe ecological consequences than either would cause independently (Rillig *et al.,* 2019).

Interactions between climate change and microplastic pollution

Climate change can significantly influence the fate and transport of microplastics in wetlands. Rising temperatures associated with global warming can accelerate the degradation of plastic materials, potentially increasing the rate at which microplastics are generated from larger plastic debris (Romera-Castillo *et al.,* 2018). This process can lead to a higher concentration of smaller plastic particles, which have greater ecological impacts due to their increased bioavailability and potential for ingestion by a wider range of organisms (Koelmans *et al.,* 2015). Changes in precipitation patterns and increased frequency of extreme weather events, both consequences of climate change, can alter the hydrological dynamics of wetlands. This can result in modified transport and distribution patterns of microplastics within these ecosystems (Hurley *et al.,* 2018). Increased flooding events may lead to the remobilization of microplastics from sediments and their subsequent transport to new areas, potentially expanding the spatial extent of microplastic pollution (Bondelind *et al.,* 2019). Conversely, microplastic pollution can exacerbate some of the effects of climate change on wetland ecosystems. Microplastics have been shown to affect soil structure and water retention capabilities, which could potentially alter the carbon sequestration capacity of wetlands (de Souza Machado *et al.,* 2018). Because wetlands are significant carbon sinks, any reduction in their ability to store carbon could contribute to further accelerating climate change.

Microplastics can serve as vectors for the transport of other pollutants, including persistent organic pollutants (POPs) and heavy metals (Brennecke *et al.,* 2016). Changes in temperature and pH caused by climate change may affect the adsorption and desorption rates of these pollutants on microplastics, potentially increasing their bioavailability and toxicity to wetland organisms (Hartmann *et al.,* 2017). The interaction between microplastics and climate change can also have indirect effects on wetland ecosystems through impacts on key species and food webs. Microplastics have been shown to affect the growth and photosynthetic efficiency of some aquatic plants and algae (Xu *et al.,* 2020). Combined with the physiological stress caused by changing climate conditions, this could lead to shifts in primary productivity and community composition in wetland ecosystems. Understanding these interactions is crucial for developing effective management strategies and predicting the long-term impacts on wetland ecosystems. Future research should focus on quantifying these synergistic effects and exploring potential feedback mechanisms between these two major environmental stressors.

Effects of climate change on cyanobacterial blooms

Climate change is increasingly recognized as a major driver of cyanobacterial bloom dynamics in wetland ecosystems. The synergistic interactions between climate change and cyanobacterial blooms are complex and multifaceted, often leading to more frequent, intense, and persistent bloom events (Paerl & Huisman, 2009). Rising temperatures, a major consequence of climate change, directly benefit many cyanobacterial species. This temperature-dependent growth response is particularly pronounced in species such as *Microcystis*, a common bloom-former in freshwater systems (Visser *et al.,* 2016). As global temperatures continue to rise, the geographic range and duration of conditions favourable for cyanobacterial growth are expected to expand, potentially leading to blooms in regions where they were previously rare or absent (Chapra *et al.,* 2017).

Climate change is also affecting precipitation patterns, leading to more frequent and intense extreme weather events. Increased rainfall and subsequent runoff can increase nutrient loading of wetlands, particularly nitrogen and phosphorus, which are essential for cyanobacterial growth (Moss *et al.,* 2011). Conversely, drought periods can lead to reduced water levels and increased water residence time, conditions that favour cyanobacterial dominance (Jöhnk *et al.,* 2008). The alternation between these extremes can create a “perfect storm” scenario for cyanobacterial blooms, with bursts of nutrients during wet periods followed by ideal growth conditions during dry periods (Paerl *et al.,* 2016).

Changes in the stratification of the water column, another consequence of climate change, can further promote cyanobacterial blooms. Warmer surface waters increase thermal stratification thereby reducing vertical mixing. Many cyanobacteria can regulate their buoyancy, allowing them to exploit this stratification by moving vertically to optimize their position for light and nutrients

(Carey *et al.,* 2012). This gives them a significant competitive advantage over non-motile phytoplankton species. Changes in carbon dioxide levels caused by climate change also play a role in the dynamics of cyanobacterial blooms. Increased atmospheric carbon dioxide concentrations can lead to increased dissolved CO_2 in aquatic environments, potentially benefiting certain cyanobacterial species. Some studies suggest that increasing CO_2 levels may favour toxin-producing cyanobacteria strains, although this relationship is complex and requires further research (Visser *et al.,* 2016).

The synergistic effects of climate change on cyanobacterial blooms extend beyond their frequency and intensity. Climate change can also influence the toxicity of blooms. Higher temperatures have been associated with increased production of cyanotoxins in some species (Walls *et al.,* 2018). This has significant implications for ecosystem and human health, as many of these toxins can cause severe illness or death in animals and humans. Furthermore, the interaction between climate change and cyanobacterial blooms can create feedback loops that exacerbate both problems. Cyanobacterial blooms can increase water turbidity, leading to higher water temperatures as more heat is trapped near the surface. This, in turn, can promote further bloom development (Paerl & Huisman, 2008).

Microplastics and Cyanobacteria: A Dangerous Alliance

The interaction between microplastics and cyanobacteria in wetland ecosystems represents a complex and potentially hazardous relationship that is gaining increasing research attention. This alliance has the potential to increase the negative impacts of both stressors on wetlands and aquatic life. Through the interaction between microplastics and cyanobacteria, microplastics can serve as a substrate for the colonization of cyanobacteria. Studies have shown that various cyanobacterial species can readily attach to microplastic surfaces and form biofilms (Oberbeckmann *et al.,* 2015). This colonization process, known as “plastisphere” formation, can change the properties of microplastics and influence their fate in aquatic environments (Zettler *et al.,* 2013). The plastisphere can provide a stable growth surface and protection from grazing for cyanobacteria, potentially enhancing their survival and proliferation in wetland ecosystems (Rummel *et al.,* 2017). The formation of cyanobacterial biofilms on microplastics can also influence the buoyancy and transport of these particles in water bodies. When cyanobacteria colonize microplastics, they can change the density and surface properties of the particles, influencing their distribution and residence time in the water column (Lagarde *et al.,* 2016). This interaction could potentially lead to changes in the spatial patterns of both microplastic pollution and cyanobacterial blooms in wetlands. The association between microplastics and cyanobacteria may impact the production and distribution of cyanotoxins. The presence of microplastics may stimulate toxin production in certain cyanobacterial species. Microplastics colonized by toxin-producing cyanobacteria could act as vectors for the transport and dispersal of these toxins in aquatic ecosystems, potentially expanding the spatial reach of their harmful effects (Bellingeri *et al.*, 2020).

The interaction between microplastics and cyanobacteria also has potential impacts on nutrient cycling in wetland ecosystems. Cyanobacterial biofilms on microplastics can influence the adsorption and desorption of nutrients, particularly phosphorus, which is often a limiting nutrient for cyanobacterial growth (Zhang *et al.,* 2020). This could create localized zones of nutrient enrichment around microplastic particles, potentially promoting cyanobacterial growth and bloom formation. The presence of microplastics can influence the community composition of cyanobacterial blooms. Different cyanobacterial species may have varying affinities for colonizing microplastic surfaces, which could lead to shifts in the dominant species within blooms (Miao *et al.,* 2019). This could have cascading effects on ecosystem functioning and potentially alter the toxicity profiles of cyanobacterial blooms.

The dangerous alliance between microplastics and cyanobacteria also extends to their combined effects on aquatic organisms. Microplastics colonized by cyanobacteria may be more likely to be ingested by aquatic organisms due to their resemblance to food particles (Seeley *et al.*, 2020). This could lead to increased exposure to microplastics and cyanotoxins, potentially increasing the negative impacts on organism health and survival. The interaction between microplastics and cyanobacteria can impact water treatment processes. Cyanobacterial biofilms on microplastics could potentially protect the bacteria from disinfection treatments, making it more challenging to manage water quality in affected systems (Wu *et al.*, 2019).

Cumulative Impacts on Wetland Ecosystem Functioning

Wetland ecosystems face an unprecedented combination of stressors that threaten their ecological integrity and functionality. Climate change, microplastic pollution, and cyanobacterial blooms have emerged as three major challenges that, when interacting synergistically, can have far-reaching consequences for wetland ecosystems. These stressors do not operate in isolation but rather amplify each other’s effects, leading to complex and often unpredictable results. Climate change acts as a primary driver, altering temperature regimes and precipitation patterns in wetlands. Increased temperatures and altered hydrological cycles can create favourable conditions for cyanobacterial blooms to thrive in warmer waters (Paerl & Huisman, 2008). Simultaneously, extreme weather conditions caused by climate change may increase the transport of microplastics into wetland systems through increased runoff and flooding (Horton & Dixon, 2018).

Microplastics in wetland environments can serve as vectors for harmful algal bloom species, including cyanobacteria. These plastic particles provide surfaces for bacterial colonization and can potentially transport cyanobacteria to new habitats (Yokota *et al.,* 2017). Microplastics may release chemical additives or adsorb other pollutants, which can stimulate cyanobacterial growth or increase their toxicity (Zhang *et al.,* 2020). Cyanobacterial blooms, fueled by both climate change and microplastic pollution, can have devastating effects on wetland ecosystems. They can deplete oxygen levels, release toxins, and alter food web dynamics (O'Neil *et al.,* 2012). The presence of cyanobacterial blooms can also exacerbate the impacts of climate change by reducing water clarity and increasing surface water temperatures, creating a positive feedback loop (Huisman *et al.,* 2018).

The cumulative impact of these three stressors on wetland ecosystem functioning is multifaceted. They can disrupt nutrient cycling, alter primary productivity, and lead to biodiversity loss (Saaristo *et al.,* 2018). The synergistic effects can also affect the ecosystem services provided by wetlands, such as water purification, carbon sequestration, and providing habitats for various species (Grizzetti *et al.,* 2019). Understanding these complex interactions is crucial for developing effective management strategies to protect and restore wetland ecosystems. Future research should focus on elucidating the mechanisms behind these synergistic effects and quantifying their long-term impacts on wetland functioning and resilience (Green *et al.,* 2017).

Disruptions in Biogeochemical Cycles

Wetlands play a crucial role in global biogeochemical cycles, particularly in carbon, nitrogen, and phosphorus cycles (Mitsch & Gosselink, 2015). Climate change, microplastic pollution, and cyanobacterial blooms can significantly alter these cycles, leading to cascading effects throughout the ecosystem. Climate change is a major cause of disruptions in biogeochemical cycles. Rising temperatures can accelerate microbial decomposition and potentially increase the release of stored carbon from wetland soils (Kayranli *et al.,* 2010). This shift could transform wetlands from carbon sinks to carbon sources, exacerbating climate change in a positive feedback loop. Altered hydrological regimes due to climate change can affect nutrient cycling. More frequent drought events may lead to increased oxidation of organic matter, releasing stored nutrients and potentially causing eutrophication when water levels rise again (Jeppesen *et al.,* 2015).

Microplastics lead to a novel disruption to biogeochemical cycles in wetlands. These small plastic particles can affect nutrient cycling by altering microbial communities responsible for decomposition and nutrient conversion (Seeley *et al.,* 2020). Microplastics may also serve as vectors for pollutants, potentially introducing toxic substances into biogeochemical cycles and food webs (Li *et al.,* 2018). The long-term impacts of microplastics on wetland biogeochemistry are still unclear, but early evidence suggests they could have a significant influence on nutrient availability and cycling.

Cyanobacterial blooms, often exacerbated by climate change and nutrient pollution, can cause dramatic changes in biogeochemical cycles. These blooms can lead to fluctuations in dissolved oxygen levels and produce hypoxic or anoxic conditions that alter redox-sensitive biogeochemical processes (O'Neil *et al.,* 2012). Cyanobacterial blooms can affect pH levels, influencing the solubility and bioavailability of various nutrients and potentially toxic elements (Huisman *et al.,* 2018). The nitrogen cycle is particularly vulnerable to these stressors. Changes in temperature and humidity caused by climate change can affect the rates of nitrogen fixation, nitrification, and denitrification (Bai *et al.,* 2013). Microplastics can disrupt the microbial communities responsible for these processes, while cyanobacterial blooms can lead to increased nitrogen fixation and altered nitrogen cycling dynamics (Finlay *et al.*, 2013). These disruptions in biogeochemical cycles can have cascading effects on wetland ecosystem services. Changes in the carbon cycle could influence the global climate regulation service provided by wetlands. Changes in biogeochemical cycles can affect primary productivity and food web dynamics, potentially altering biodiversity and ecosystem structure (Erwin, 2009).

Challenges in Research and Monitoring

Wetland ecosystems are inherently complex, and the interplay between climate change, microplastics, and cyanobacterial blooms presents significant challenges for researchers and environmental managers. These stressors do not act in isolation but rather interact in ways that can be synergistic, antagonistic, or additive (Ormerod *et al.,* 2010). Rising temperatures due to climate change may accelerate the degradation of microplastics, potentially releasing more toxic compounds into the environment (Rodrigues *et al.*, 2019). Simultaneously, these conditions can favour the growth of cyanobacteria, which in turn can interact with microplastics through adsorption or as vectors for dispersal (Lagarde *et al.,* 2016). Deciphering the individual and combined effects of these stressors requires sophisticated experimental designs and analytical approaches that can account for multiple variables and their interactions.

Traditional research methods often struggle to capture the full complexity of multi-stressor environments in wetlands. Many studies focus on single stressors or simplified combinations, which may not accurately reflect real-world conditions (Jackson *et al.*, 2016). When it comes to microplastics, current sampling and analysis techniques have limited ability to detect and quantify smaller particles, particularly nanoplastics, which may have significant ecological impacts (Koelmans *et al.,* 2015). In the case of cyanobacterial blooms, traditional monitoring methods based on visual observation or chlorophyll-a measurements may not provide timely or accurate information on bloom dynamics and toxin production (Huisman *et al.,* 2018).

Emerging Technologies and Approaches

To address these challenges, researchers are developing and implementing new technologies and methods. Remote sensing and satellite imagery are increasingly used to monitor cyanobacterial blooms over large spatial scales and at higher temporal resolution (Urquhart *et al.*, 2017). For microplastics, advanced spectroscopic techniques such as Raman and Fourier-transform infrared (FTIR) spectroscopy are improving the detection and characterization of smaller particles (Primpke *et al.*, 2020). In climate change research, high-resolution climate models and downscaling techniques improve the accuracy of predictions (Ekström *et al.*, 2015). Integrative approaches, such as the use of environmental DNA (eDNA) metabarcoding, provide new insights into community-level responses to multiple stressors (Pawlowski *et al.*, 2018). The application of machine learning and artificial intelligence in data analysis helps researchers identify complex patterns and relationships in large environmental datasets (Hampton *et al.*, 2013). Despite these advancements, challenges remain in standardizing methods, integrating data from different sources, and translating research findings into effective management strategies. Collaborative, interdisciplinary research efforts and the development of comprehensive monitoring programs will be crucial in addressing the complex interactions between climate change, microplastics, and cyanobacterial blooms in wetland ecosystems.

Conclusion:

The convergence of climate change, microplastic pollution, and cyanobacterial blooms poses a complex and urgent challenge for wetland ecosystems worldwide. This trifecta of stressors interacts in ways that often amplify their impacts, potentially leading to severe ecological consequences. Climate change acts as a catalyst, altering temperature regimes and precipitation patterns that influence both the degradation of microplastics and cyanobacterial proliferation. Microplastics serve as potential vectors for harmful algal bloom species and associated toxins, while also affecting nutrient cycling in ways that may promote bloom formation. Addressing this trifecta of stressors requires a multifaceted approach that combines mitigation, adaptation, and restoration strategies. Efforts to reduce greenhouse gas emissions, improve plastic waste management, and control nutrient inputs are all critical components of a comprehensive solution. The development and implementation of novel monitoring techniques and predictive models will be essential for the early detection and management of these interacting stressors.

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IMPACT OF HEAVY METAL POLLUTION ON PHYTOCHEMICAL CONSTITUENTS OF *SENNA AURICULATA* COLLECTED FROM THE POLLUTED ENVIRONMENT

R. Nagalakshmi*[1] and S. P. Anand[2]
[1]Department of Botany, Srimad Andavan Arts and Science College,
Affiliated to Bharathidasan University, Tiruchirappalli-620005, Tamil Nadu, India
[2]PG and Research, Department of Botany, National College,
Affiliated to Bharathidasan University, Tiruchirappalli-620001, Tamil Nadu, India.
Corresponding author E-mail: nagalakshmi.93botany@gmail.com, dranandsp@gmail.com

Abstract:

Plants' bioactive chemical synthesis changed when they were subjected to pollution stress. The purpose of this study was to compare the qualitative and quantitative phytochemical evaluation of *Senna auriculata* leaves and flowers obtained from unpolluted and polluted areas. The presence of carbohydrates, glycosides, alkaloids, proteins, phenolic compounds, flavonoids, tannins, steroids & triterpenoids, and saponins were determined using the standard technique. The quantitative study was performed to estimate the levels of phenols, flavonoids, tannins, and saponins. The results revealed that there was a higher concentration of bioactive compounds than at contaminated areas. Atomic absorption spectroscopy was used to identify heavy metals such as Pb, Cr, and Cd. Analytical results demonstrate that samples C and D from contaminated sources had greater levels of heavy metals than samples A and B from unpolluted sources. To further understand the association between heavy metal levels and phytocompounds, Pearson's correlation analysis was used. The findings show a moderately significant negative association between heavy metal concentrations and the amount of phenols, flavonoids, tannins, and saponins in the leaves and flowers. This might be due to heavy metal contamination influencing the phytochemical characteristics of plants in contaminated areas. Based on this fact, it is proposed that medicinal plants used in medicines be harvested from an unpolluted area wherever possible.

Keywords: Heavy Metals, Phytochemical Screening, Polluted Sites, *S. auriculata,* Unpolluted Sites

Introduction:

Medicinal herbs are a gift from nature that gives a variety of health advantages. Many modern medicines are derived from plants, which are also a rich source of natural medicines. Looking back over 2000 years of medical history, plants have been primarily employed as the best source of medicine (Nostro *et al.* 2000). Herbal drugs are a more natural and safer alternative to synthetic drugs (Dineshkumar and Rajakumar 2015). The importance of plants lies in their active ingredients, which are the real healers in the medication process. Phytoconstituents are naturally occurring, biologically active chemical substances found in plants as primary and secondary metabolites. Primary metabolites include chlorophyll, proteins, and common sugars whereas secondary metabolites include alkaloids, phenols, terpenoids, tannins, saponins, flavonoids, steroids, and glycosides (Fouda *et al.* 2009). In the pharmaceutical sector, phytochemicals are critical for the development of new drugs as well as the production of therapeutics, food additives, and agrochemicals (Starlin *et al.* 2019). As a result, the necessity to investigate the phytochemicals of numerous plants has grown exponentially. Qualitative Phytochemical Screening will help elucidate the phytochemicals present in each plant, while quantification of these secondary metabolites will enable the extraction, purification, and identification of bioactive substances for convenient utilization.

Wild medicinal plants are continually exposed to pollutants, either directly or indirectly, and therefore it is more difficult to control all potential sources of environmental pollution. When air, soil, or water pollution contaminates the plants from which herbal medicines are derived, it affects the physiology and biochemical properties of the plant. Secondary metabolite production changes in plants exposed to pollution stress. Abiotic stress can affect medicinal plants' metabolic profiles and developmental trajectories, resulting in increased synthesis of diverse secondary metabolites (Jonnada *et al.* 2015). Heavy metal pollution changes the chemical content of plants, which can harm the effectiveness and quality of plant products. Metal absorption can cause considerable morphological and metabolic changes in plants. Many of these modifications are thought to be adaptive responses to metal stress (Sarma 2011). Plant species, microclimate conditions, environmental pollution, and other aspects all influence the amounts of these metals in plants (Broadley *et al.* 2007). There is a significant risk of heavy metal contamination in medicinal plant species obtained from industrial sites (Sarma *et al.* 2012). As a result, there is a considerable chance of harmful metal presence in plant parts while extracting physiologically active compounds from plants growing in these polluted regions.

A phytochemical analysis can be used to investigate the various biochemical changes that occur within a plant. This can be accomplished by conducting a comparative investigation of plants collected from unpolluted and polluted areas. Such comparative studies, however, have yet to be conducted on one of the important medicinal plants, *Senna auriculata* (L.) Roxb belongs to the Fabaceae family and is commonly known as Tanner’s cassia (Nadkarni 2002). It has been generally utilized in conventional medicine as a powerful assistant in the treatment of diabetes mellitus, rheumatism, and conjunctivitis (Joshi 2000; Kirtikar and Basu 2006). The plant is also known to have antioxidants, antihyperlipidemic (Kumaran and Karunakaran 2007), hepatoprotective (Umadevi *et al.* 2006), antipyretic (Joy *et al.* 2012), and antimicrobial activity (Latha and Pari 2003). Therefore, this study aimed to compare the qualitative and quantitative phytochemical analysis of the leaves and flowers of *S. auriculata* collected from unpolluted and polluted sites

Materials and Methods:

Plant Collection and Identification

In June 2021, *Senna auriculata* (L.) Roxb. leaves and flowers were collected from both pristine and contaminated locations. The unpolluted sites included the Pachaimalai Hills and Kolli Hills, while the polluted areas were Avur Road and Samayapuram Kariyamanickam Road, with numerous industrial facilities situated within 500 m of these locations. The plant specimens were verified and confirmed by the Southern Regional Center of the Botanical Survey of India in Coimbatore 641 003, with reference number BSI/SRC/5/23/2021/Tech-166.

Preparation of Plant Extract

The plant specimens were left to air dry in a shaded area for several days before being processed into a rough powder using an electrical grinding device. This coarse material was then subjected to successive ethanol extractions using a Soxhlet apparatus. Following filtration, the resulting extract underwent evaporation using a rotary evaporator. The final dried extracts were stored under refrigerated conditions for subsequent analysis.

Qualitative Phytochemical Studies

Researchers have conducted a preliminary phytochemical analysis of ethanol extracts derived from the leaves and flowers of *S. auriculata*. The investigation aimed to identify the presence of various compounds, including carbohydrates, glycosides, alkaloids, proteins, phenolic compounds, flavonoids, tannins, steroids, triterpenoids, and saponins. The qualitative assessment followed the methodology outlined by Harborne (1984).

Carbohydrates (Molisch's test): A 1% alcohol-naphthol solution was applied to the extract, using 2-3 drops. Following this, 2 ml of concentrated sulfuric acid was gently introduced down the sides of the test tube. The formation of a purple ring at the interface between the two liquids indicated the carbohydrates.

Glycosides (Borntrager's test): A minimal amount of hydrolyzed sample was vigorously combined with chloroform and left undisturbed until the chloroform layers were segregated. The resulting chloroform layer was then exposed to an equivalent volume of a diluted ammonia solution. The formation of a pink hue in the ammonia layers shows the availability of glycosides.

Alkaloids (Mayer's test): A small amount of the sample was combined with a few drops of dilute HCl, mixed thoroughly, and passed through a filter. The resulting liquid was then exposed to Mayer's reagent, which consisted of potassium mercuric iodide in a solution. The cream-colored precipitation shows the availability of alkaloids.

Proteins (biuret test): Combine 2 mL of extract with an equal volume of biuret reagent, which consists of 5% sodium hydroxide and 1% copper sulfate solutions. The pale pink or violet coloration shows the availability of alkaloid

Phenols (ferric chloride test): A minute quantity of sample was independently liquefied in H_2O. The resulting dilute solutions were subsequently treated with a 5% $FeCl_3$ solution. The emergence of a purple coloration signified the existence of phenolic substances.

Flavonoids (alkaline reagent): Some drops of sodium hydroxide (NaOH) were added to the sample. The appearance of different colors indicates the presence of specific compounds: a violet hue suggests anthocyanins, a yellow shade points to flavones, and a yellow to orange tint signifies flavonoids.

Tannins (gelatin test) A gelatin solution (1%) with sodium chloride (10%) was added to the diluted extract. White precipitation indicates the tannins.

Steroids and triterpenoids (Libermann-Burchard test): The specimen was warmed with a minimal quantity of acetic anhydride and left to cool. Highly concentrated H_2SO_4 was then added to the test tube, causing the development of a brown ring at the point where the substances met. The composition turned green, indicating the likely presence of steroid compounds, and subsequently became deep red, suggesting the presence of triterpenoid substances.

Saponins (foam test): To detect the presence of saponins, the plant samples were extracted using water and ethanol. The extracts were then mixed with distilled water (20ml) in a measuring cylinder and agitated for 15 minutes.1 cm froth layer on top of the liquid surface indicates the presence of saponins.

Quantitative Phytochemical Studies

Estimation of Phenols

A 1 ml extract sample was placed in a test tube with 2 ml of 20% Na_2CO_3 and 1 ml of Folin-phenol reagent. After thoroughly mixing, the solution was boiled in boiling water for 1 minute. After cooling, the resulting blue fluid was diluted with distilled water to a level of 25 mL. A variety of gallic acid solutions (20, 40, 60, 80, and 100µg/ml) were produced ahead of time. The samples were incubated at 30 degrees Celsius for 90 minutes. A UV-visible spectrophotometer was then used to measure the absorbance of both the test and standard solutions at 550 nm in comparison to a reagent blank. The total phenolic component concentration was calculated as mg GAE/g extract (Selvakumar *et al.* 2019).

Estimation of Flavonoids

The aluminum chloride technique was employed to ascertain the overall flavonoid concentration within the extracts (Hossain and Nagooru, 2011). This procedure entailed the amalgamation of 1 ml of the extract with 4 ml of deionized water and 0.3 ml of a 10% sodium nitrate solution. Following a resting period of five minutes, 0.3 ml of a 10% $AlCl_3$ solution was subsequently added. The resultant mixture was permitted to stand for one minute prior to the introduction of 2 ml of a 1M NaOH solution. The test tube was rigorously agitated to facilitate thorough mixing of the reagents, and allowed to settle. Thereafter, the optical density (OD) was quantified at 510 nm. An 80% methanol solution acted as the blank, while rutin was utilized as the standard for the formulation of the calibration curve. The total flavonoid concentration within the extracts was determined through the standard curve and articulated as mg/g of the extract.

Estimation of Tannins

The Folin-Ciocalteu methodology was utilized to ascertain the concentration of tannins (Selvakumar *et al.* 2019). This protocol entailed the amalgamation of 0.1 ml of the plant extract with 7.5 ml of distilled water within a 10 ml volumetric flask, followed by the incorporation of 0.5 ml of Folin-Ciocalteu phenolic reagent and 1 ml of a 35% Na_2CO_3 solution. Subsequently, the resultant mixture was diluted to a final volume of 10 ml with distilled water, thoroughly homogenized, and maintained at a temperature of 30 °C for a duration of 30 minutes. A series of gallic acid solutions (20, 40, 60, 80, and 100 µg/ml) was crafted employing an analogous technique. An ultraviolet-visible spectrophotometer was employed to ascertain the optical density of both the standard and experimental solutions, as well as a blank control, at a wavelength of 725 nm. The overall tannin concentration in the extract was articulated as mg GAE/g.

Estimation of Saponins

The samples (10 ml) were introduced into an Erlenmeyer flask containing 100 ml of a 20% aqueous ethanol solution, followed by heating in a hot water bath at 55°C for 4 hours with continuous stirring. After filtration, the residue was re-extracted with 200 ml of 20% ethanol, and the resultant extracts were concentrated to 40 ml at approximately 90°C. The concentrate was subsequently mixed with 20 ml of diethyl ether, whereupon the aqueous layer was retained while the ether layer was discarded, and this purification process was reiterated, concluding with the introduction of 60 ml of n-butanol and subsequent washing and drying of the extracts (Obadoni and Ochuko, 2001).

Heavy Metal Analysis

The powdered foliage and blossoms of *S. auriculata* are composed of elements such as lead (Pb), chromium (Cr), and cadmium (Cd). The wet digestion technique is acknowledged as the most efficacious method for plant materials, wherein a 2.0 g sample is combined with a nitric-hydrochloric acid mixture, subsequently heated and filtered before analysis. The National College Instrumentation Facility at National College Tiruchirappalli employed Atomic Absorption Spectroscopy (THERMO SCIENTIFIC- ice 3000) for the quantification of heavy metal concentrations, with each sample and standard solution undergoing triplicate testing.

Data Analysis

The mean and standard deviation of heavy metal concentrations were determined across three replicates, with data processing and analysis executed via Microsoft Excel 2013 and SPSS 16.0; a one-way analysis of variance was performed to evaluate the statistical significance of the results, deemed significant at $p < 0.05$, while Pearson's correlation analysis was employed to investigate the relationship between heavy metal concentrations and plant phytocompounds.

Results and Discussion:

Any crude drug extracted with a certain solvent yields a solution containing various phyto-components. The composition of these phyto-components in each solvent provides preliminary information about the quality of a medicinal sample. The presence or absence of a specific component is critical in determining the therapeutic capabilities of the plant. The qualitative phytochemical analysis of the ethanol extract of *S. auriculata* leaves and flowers was shown in **Table 1: The samples collected from the unpolluted sources reveal the presence of more compounds than the polluted sources (Fig. 1).**

Table 1: Qualitative phytochemical analysis of *S. auriculata*

Constituents	**Leaf Extract**				**Flower Extract**			
	A	**B**	**C**	**D**	**A**	**B**	**C**	**D**
Carbohydrates	+	+	+	+	+	+	+	+
Glycosides	+	+	+	-	+	+	-	+
Alkaloids	+	+	+	+	+	+	+	-
Proteins	+	+	-	+	+	+	-	+
Phenolic compounds	+	+	+	+	+	+	+	+
Flavonoids	+	+	+	+	+	+	+	+
Tannins	+	+	+	+	+	+	+	+
Steroids and Triterpenoids	+	+	-	-	+	+	+	+
Saponins	+	+	+	+	+	+	+	+

+ = present; - =absent; A & B - unpolluted sites; C & D - polluted site

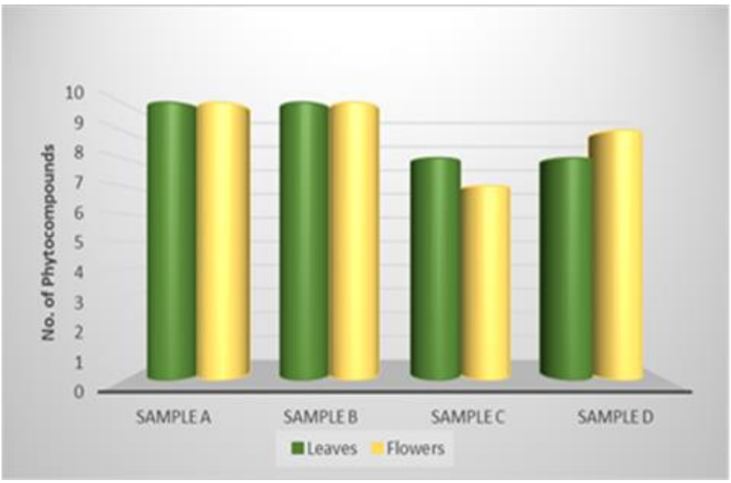

Figure 1: Comparison of qualitative phytochemical study of *S. auriculata* leaf and flower extract

This study revealed that ethanol was the most effective solvent for extracting the active phytoconstituents from *S. auriculata*. Quantitative evaluation is a crucial factor in establishing crude drug standards (Trease and Evans, 2002). The results of quantitative phytochemical analysis of the ethanol extract of *S. auriculata* were presented in Table 2.

The mean concentrations of heavy metals such as Pb, Cr, and Cd in leaves and flowers of *Senna auriculata* have been presented in Table 3.

Table 2: Quantitative phytochemical analysis of *S. auriculata*

Constituents	**Leaf Extract (mg/g)**			
	A	**B**	**C**	**D**
Phenols	153.42	149.12	67.52	58.41
Flavonoids	149.47	155.56	79.24	52.78
Tannins	91.23	76.13	35.11	14.53
Saponins	34.42	24.65	12.87	10.31
	Flower Extract (mg/g)			
Phenols	158.37	153.42	60.81	45.21
Flavonoids	129.16	161.42	82.14	56.40
Tannins	101.73	68.11	39.23	20.51
Saponins	37.15	27.32	12.35	10.04

Table 3: Heavy metal concentrations in *Senna auriculata*

Samples	**Plant parts**	**Concentrations (Mean ± SD) (mg/kg)**		
		Pb	**Cr**	**Cd**
A	Leaves	1.86±0.03	0.63±0.01	0.05±0.03
	Flowers	1.02±0.01	0.42±0.01	0.03±0.01
B	Leaves	0.01±0.01	1.07±0.03	ND
	Flowers	ND	0.91±0.26	ND
C	Leaves	13.46±0.02	1.89±0.01	0.32±0.01
	Flowers	12.78±0.03	1.65±0.04	0.27±0.03
D	Leaves	7.43±0.26	3.84±0.01	0.21±0.02
	Flowers	7.38±0.37	3.06±0.02	0.19±0.02

SD Standard deviation; ND – not detected

Analytical results show that samples C and D of polluted sites had heavy metal contents higher than samples A and B of polluted sites. This could be due to heavy metal pollution from industrial sources that navigates its way to plants via soil and water.

A correlation study was performed to determine whether heavy metal concentrations have any effect on the phytocompounds in *S. auriculata*. Tables 4 and 5 show the Correlation coefficient value for heavy metal concentrations vs. phytocompound quantities. The results suggest that there was a reasonably significant negative linear association between these variables, implying that as heavy metal concentrations in plants increased, the amount of phenols, flavonoids, tannins, and saponins in the leaves and flowers decreases.

Table 4: Pearson correlation coefficient (r) between heavy metal concentrations and quantity of phytocompounds in *S. auriculata* leaves

	Pb	Cr	Cd
Phenols	-0.849*	-0.787*	-0.906*
Flavonoids	-0.755*	-0.875*	-0.827*
Tannins	-0.697*	-0.912*	-0.777*
Saponins	-0.806*	-0.832*	-0.871*

*Correlation is significant at the 0.05 level.

Table 5: Pearson correlation coefficient (r) between heavy metal concentrations and quantity of phytocompounds in *S. auriculata* flowers

	Pb	Cr	Cd
Phenols	-0.879*	-0.902*	-0.926*
Flavonoids	-0.801*	-0.855*	-0.869*
Tannins	-0.724*	-0.935*	-0.772*
Saponins	-0.828*	-0.894*	-0.863*

The pharmacological activities of the plant extracts are attributable to the presence of secondary metabolites such as phenols, flavonoids, glycosides, alkaloids, tannins, saponins, and so on. These bio-components are well-known for their diverse biological effects and are used to treat various types of diseases. The phenol content was more in ethanolic extract of *S. auriculata* and was followed by flavonoids, tannins, and saponins. The extracts were rich in phenol and are shown significant radical scavenging activity and also considerable iron reduction. Flavonoids have been associated with numerous pharmacological activities such as antihypertensive, anti-rheumatoid, and antimicrobial activities (Veerachari and Bopaiah, 2011). Flavonoids are diuretics and antioxidants (Essiett *et al.* 2010). Flavonoids and phenols have stimulated the interest of researchers due to their possible biological properties as antioxidants, antiestrogenic, antiinflammatory, immunomodulatory, cardioprotective, and anticarcinogenic substances (Kumar and Baskar, 2015). Furthermore, tannins are important in many biological applications due to their anti-inflammatory, cardioprotective, and antibacterial activities (Huang *et al.* 2018). Tannin promotes wound healing through a variety of biological mechanisms, including chelation of free radicals and reactive oxygen species, wound contraction, and increased capillary vessel and fibroblast development. Saponins are natural antibacterial substances with a wide range of biological activities that have proven beneficial in medicinal applications (Deshpande *et al.* 2013). The phytochemical analysis, of *S. auriculata* both qualitative and quantitative, revealed the presence of phytoconstituents which are well-known antioxidants, antidiabetics, anti-rheumatism, antimicrobial, and wound healing properties by nature.

Heavy metal content is a critical factor influencing plant response and secondary metabolism. For example, Babula and colleagues investigated the physiological reactions of *Hypericum perforatum* plants to lanthanum and cadmium overload in several tissues, most notably shoots and roots (Babula *et al.* 2015). The findings revealed a general increase in certain phenolic acids (e.g., ferulic acid) and a decrease in flavonoids (e.g., epicatechin and procyanidin), both in the shoots and the roots. Okem *et al.* (2015) noticed a similar trend as our results in a prior work on *Hypoxis hemerocallidera* subjected to cadmium and aluminium, where total phenolic and flavonoids production was greatly decreased when the plant was exposed to a combination of the two metals. Ibrahim and colleagues tested different concentrations of cadmium and copper on *Gynura procumbens* plants and found that lower levels of heavy metals enhance secondary metabolite production while higher levels of combined metals inhibit secondary metabolite synthesis in plants. This finding implies that in today's environment, where there are a lot of heavy metal pollutants in the soil, secondary metabolite synthesis may be inhibited due to interactions between these heavy metals (Ibrahim *et al.* 2017). According to Lajayer *et al.* (2017), growing medicinal plants in heavy metal contaminated habitats may eventually influence secondary metabolite production, resulting in massive changes in the amount and quality of these molecules. On comparing the results we found that from the phytochemical analysis, the plant collected from the unpolluted natural sites (A&B) had more quantity of bioactive compounds than the polluted sites (C&D). These results confirm the findings of Osman and Badawyb, (2013), who discovered that the concentration of secondary metabolites and fat in *Zygophyllum coccineum* from polluted sites was lower than in non-polluted sites. The reason for this is, of course, that plants growing in the wild, as expected, may lead to stress in these plants, causing the pathways for the synthesis of these metabolites to be affected. As a reason, the same plants growing in unpolluted areas exhibit different characteristics than those growing in highly polluted industrial areas. As a result, the variations in phytochemicals reported in these plants imply that environmental pollution is affecting the plants.

Conclusions:

The qualitative phytochemical screening is to be done before making substantial findings of compounds or medicinal substances. Its purpose is to provide concrete knowledge and study into which plant active elements have the potential to assist mankind. The phytochemical examination of *S. auriculata* obtained from unpolluted sites revealed that there were more bioactive chemicals than at polluted sites. Based on this observation, it is suggested that medicinal plants used in pharmaceuticals should preferably be collected from a natural, unpolluted environment.

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APPLICATIONS OF NANOMATERIALS IN ENVIRONMENTAL PROBLEMS AND THEIR SUSTAINABLE REMEDIATION

Aisha Siddekha*[1] and Lalithamba H. S.[2]
[1]Department of Chemistry,
Government First Grade College, B.H. Road, Tumakuru-572102, Karnataka, India,
[2]Department of Chemistry,
Siddaganga Institute of Technology, B.H. Road, Tumakuru-572 103, Karnataka, India
*Corresponding author E-mail: aishasiddekha@gmail.com

Abstract:

Over the past few years, a growing number of nanomaterials are being produced and revolutionized the world with their innumerable number of applications, which includes their environmental applications also. The growing global population is causing an increase in energy and material consumption, which has an impact on the environment. Increased air pollution from automobiles and industrial facilities, increased generation of solid waste, and contamination of surface and groundwater are a few of these effects. Through the direct application of nanoparticles for the detection, prevention, and removal of pollutants as well as the indirect application by synthesizing environmentally friendly products, nanotechnology has positive effects on the environment. Some of the products being used for this purpose are nano-filters, nano-sensors, nano-photocatalysts, magnetic nanoparticles and nano-adsorbents contributing immensely for the betterment of environment. This chapter gives the overview of use of nanomaterials in combating the environment related problems efficiently, as we explore the uses of nanotechnology for the remediation of environmental problems such as water treatment, waste management, control and reduction of different types of pollutions.

Keywords: Nanomaterials, Bioremediation, Pollution Control, Waste Management

1. Introduction:

Nanomaterials research has been the study and development of nanometer-sized objects, often with nanostructures. Nanoparticles, have highly desirable properties that are unique from those of the bulk materials. The research, on synthesis and property modification is motivated by the uses in various fields like agriculture (Dwivedi *et al.*, 2016), medicine, drug design and drug delivery (Gao *et al.*, 2013), electronics, optics, solar cells, sensors, light emitting diodes, energy storage devices (Nguyen *et al.*, 2016) and catalysis. The method of nanoparticle synthesis is an important factor in determining structural and morphological properties and the type of application.

Application of nanomaterials for environmental protection is gaining popularity in the recent times (Beni & Jabbari, 2022). The properties imparted by these nanoparticles have led to their much-discussed potential for use in a wide variety of technological solutions that are needed to address global environmental problems. Supportive data indicate that nanomaterials also have potential adverse effects on human health and the environment (Asmatulu *et al.,* 2022). We need to address the use of nanomaterials in the environment, focusing on their ability to solve both environmental problems and the impacts that these nanomaterials may have on humans and the environment. Necessarily, the type of interactions through which nanomaterials are designed to solve environmental problems affect the overall effectiveness of a method and may be favorable or may not be favorable in specific applications. This text addresses the use of nanomaterials to solve environmental problems related to toxic pollutants, which are certain to have adverse human health and environmental effects if left unchecked.

In this chapter we have presented the synthesis, applications of nanomaterials in bioremediation, controlling and reducing air and water pollution, water treatment *etc.* comprehensively.

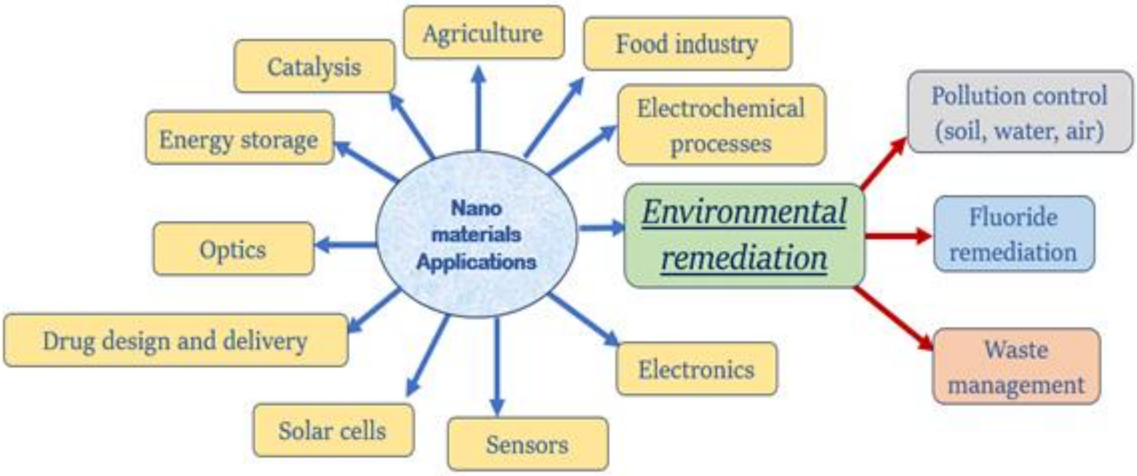

Figure 1: Applications of nanomaterials in various fields

2. Environmental Problems and Challenges

In the modern world, environmental problems are getting increasingly serious due to the rapidly growing global population and overconsumption of myriad resources. Largely, this has the effect of fouling the earth and surrounding environment to a condition whereby they cannot return to their original condition by themselves in any convenient time (Abbass et al.,2022). Foul air contributes to nearly 43 percent of pollution and acid rain. Over the past few years, nanotechnologies have emerged as a new tool for solving a variety of problems related to environmental pollution and sustainability. Therefore, in recent times there has been increased interest in using nanomaterials for the sustainable remediation of environmental problems caused by rapidly developing industries and overpopulation.

Great strides have been made in the development of new synthetic methodologies to create a myriad of novel nanomaterial architectures with structural dimensions less than 100 nm, and having a high specific surface area and/or unique physical and chemical properties. Using functionalized nanomaterials in various miniaturization devices is generally known to efficiently remediate several environmental problems caused by the waste products of chemical and allied industries in a very sustainable manner (Thakur *et al.,* 2022). This has attracted the attention of several scientists working in the environmental industry to control environmental pollution with the help of functionalized nanomaterials along with the other regular nanomaterials.

3. Synthesis of Nanomaterials for Environmental Applications

The synthesis of nanomaterials is being tailored to meet specific environmental challenges. Ongoing research focuses on improving the efficiency, sustainability, and cost-effectiveness of these nanomaterials for practical applications in solving environmental problems. *Some the synthetic methods reported include*;

The synthesis of *metal nanoparticles* (Kaur *et al.,* 2022) by Chemical Reduction using reducing agents to convert metal salts into nanoparticles (e.g., gold, silver). Sol-gel process, transitioning from a liquid solution to a solid gel, which can form nanoparticles. Laser Ablation which uses laser pulses to vaporize metal into nanoparticles.

Metal Oxide Nanoparticles (Nair et al., 2021) like TiO_2, are obtained by Co-precipitation which involves the mixing of metal salts in solution and precipitating out oxides., Hydrothermal Synthesis by utilizing high-pressure and temperature to form oxides from precursors. Solvothermal method using organic solvents.

Carbon-Based Nanomaterials (Dutta *et al.,* 2022*)* like Graphene, carbon nanotubes, carbon dots etc. are synthesized by Chemical Vapor Deposition (CVD) which involves the deposition of carbon from gas-phase precursors onto a substrate. Arc Discharge method is used for generating nanoparticles from carbon vaporized by electrical discharge. Liquid-phase Exfoliation for dispersing bulk graphite in a solvent to produce graphene.

Polymeric Nanomaterials (Darwish *et al.*, 2022) are prepared by Emulsion Polymerization creating nanoparticles through the polymerization of monomers in an emulsion. And Electrospinning is used in producing nanofibers from polymer solutions under an electric field. These serve as carriers for slow-release of nutrients or pollutants and in membrane technology.

Silica Nanoparticles (Nayl *et al.,* 2022) are prepared by the *Stöber Process* (Ren *et al.,* 2020) by the controlled hydrolysis and condensation of silanes to form silica nanoparticles. Another method is the *Template method* which uses the porous materials as templates to create silica structures. These are used in adsorption of pollutants and also as carriers for drug delivery.

Hybrid Nanomaterials or *composites* (Gamage *et al.,* 2022) are being used for enhanced photocatalysis, gas-sensing, and pollutant adsorption. These are being prepared by the *Layer-by-Layer Assembly* by depositing materials alternately to create composite nanostructures**. *In Situ*** *synthesis* of composites is carried out by incorporating metal nanoparticles into a polymer matrix during polymerization.

4. Nanomaterials for Environmental Remediation

4.1. Water Pollution and Application of nanomaterials in Water and Wastewater Treatment

Water is essential to life, even though it is a simple molecule, it can pose serious threats to our own well-being and to the survival of our planet. Many signs of the environmental damage done by the production and processing of goods appear in water. Chemicals are discharged into waterways by factories, mines, wells, and slaughterhouses. Houses, buildings, and sometimes factories discharge human waste. Fertilizer and pesticides are dissolved by rain and contribute to acid rain and to agricultural runoff. The direct disposal of waste from foundries, chemical companies, and other manufacturing plants are being monitored (Suaad Hadi Hassan Al-Taai, 2021). The mining and disposal of the earth's resources cause toxic heavy metals to be released in to water and causing water pollution at an alarming rate. Globally, more than 1.1 billion people lack access to safe drinking water.

Water sustains all life on Earth, undoubtedly, animals, plants, microbes and human beings rely on water for their survival. In addition, water is necessary for the weather systems that filter toxins from the air, distribute heat and water around the Earth.

Nanomaterials have shown great promise in treating water pollution due to their unique properties and high surface area-to-volume ratio. Nanomaterials like carbon nanotubes and graphene oxide can effectively adsorb contaminants such as heavy metals, dyes, and organic pollutants from water due to their high surface area (Arora & Attri, 2020). Nanoparticles can act as catalysts to accelerate chemical reactions that break down pollutants. For example, titanium dioxide nanoparticles are used in photocatalysis to (Dharma *et al.,* 2022) degrade organic pollutants under UV light. Next the Nanofilters (Fahimirad *et al.,* 2020), made from materials like nanosilica or nanofibers, can efficiently remove bacteria, viruses, and other microorganisms from water, improving its safety for consumption. Nanosensors (Javaid *et al.,* 2021) can detect trace amounts of pollutants, providing real-time monitoring of water quality as the early detection can help to mitigate contamination. Nano-coatings that incorporate nanomaterials can be applied to surfaces to prevent biofouling and enhance the removal of pollutants (Kumar *et al.,* 2021). Apart from this, nanoparticles can be used to enhance the activity of microorganisms that degrade pollutants, making bioremediation processes more efficient.

Overall, the integration of nanomaterials in water treatment systems offers innovative solutions to combat various types of water pollution, making them a significant area of research and application

4.2. Air Pollution and use of nanomaterials for Air Purification

Air pollution is a significant global issue, impacting health, the environment, and climate. Traditional air purification methods, like filters and chemical scrubbers, have limitations, leading to interest in advanced technologies, including nanomaterials. An overview of air pollution reveals the major sources of pollution vehicle emissions, industrial activities, burning of fossil fuels, and agricultural practices (Afifa *et al.,* 2024).

Air pollutants can cause respiratory diseases, cardiovascular problems, and even cancer. Also, environmental Impact of air Pollution is, it contributes to climate change, harms ecosystems, and reduces biodiversity. We come across, Nanomaterials being used in Air Purification, due to their unique properties, offer innovative solutions for air purification.

Nanoparticles with their a large surface area relative to their volume, allow for a greater interaction with pollutants. Some nanomaterials, like titanium dioxide (TiO_2) and zinc oxide (ZnO), can catalyze chemical reactions that break down pollutants (O'neill *et al.,* 2023), including volatile organic compounds (VOCs) and particulate matter. Nanomaterials can effectively adsorb gases and particles. For example, activated carbon nanoparticles can capture a wide range of harmful substances. Under UV light, certain nanomaterials can generate reactive species that degrade organic pollutants in the air.

4.3. Soil Contamination and using nanomaterials for soil remediation

Soil contamination remains a significant environmental issue today, driven by various factors (Zhang *et al.,* 2023) like unscientific agricultural practices, rampant industrial activities, uncontrolled urban development and improper waste disposal in landfills etc. which impart heavy metals, pesticides, hydrocarbons, mineral oils etc. (Paz-Ferreiro *et al.,* 2018). Addressing soil contamination is critical for sustainable land use, public health, and environmental protection. Various techniques, such as bioremediation, phytoremediation, and soil washing, are being used to clean contaminated soils. Policy (Hou *et al.,* 2020) initiatives and regulations are also being developed to prevent and manage contamination. Using nanomaterials for soil remediation is a promising area of research aimed at addressing soil contamination from heavy metals, pesticides, and organic pollutants (Rajput *et al.,* 2022). Some important factors regarding the application of metal-based nanoparticles like, zero-valent iron, silver, and gold can adsorb, degrade, or transform contaminants (Sathish *et al.,* 2023). Nano-clays (Iravani et al, 2022) can improve soil structure and enhance the retention of pollutants, facilitating their removal and Carbon Nanomaterials (CNMs) such as graphene and carbon nanotubes, which can adsorb organic pollutants in soil very effectively. Mechanism of action includes the adsorption or binding of contaminants on to nanoparticles due to their surface area, and hence reducing the bioavailability of the contaminants. Some nanomaterials can catalyze reactions that break down harmful substances into less toxic forms. Nanoparticles can also enhance the mobility of pollutants in soil, allowing for easier extraction or degradation.

Advantages of using nanomaterials in soil bioremediation are: i) Increased efficiency of the soil, as the nanomaterials often have higher reactivity and surface area in comparison with the bulk materials, making them more effective. (ii) Targeted Remediation is another selective advantage as nanomaterials can be designed to target specific pollutants, reducing overall environmental impact. (iii) Their use can potentially reduce the number of chemical reagents needed, leading to less waste generation.

Challenges to be explored include**,** environmental Impact of the long-term effects of introducing nanomaterials into soil ecosystems are need to be fully understood. Next the Regulatory issues (Almeida *et al.,* 2020) about using the use of nanotechnology in environmental applications is subject to varying regulations, which can hinder development and implementation. Most importantly cost of production and application of nanomaterials can be expensive, although costs may decrease with advancements in technology and easily available to a common man (Pandey & Jain, 2020b).

Future directions include the investment in Research and Development, and continued research is needed to optimize the types of nanomaterials used and their applications in different soil types and contamination scenarios so as to reap the rewards in a right manner. This may include the field trials or field studies essentially to understand the practical implications of using nanomaterials in real-world settings. The sustainable practices which will integrate nanotechnology with other remediation strategies could enhance effectiveness while minimizing negative impacts. Using nanomaterials for soil remediation holds great potential, but careful consideration of their environmental impact and regulatory frameworks is crucial for a successful implementation.

4.4. Hazards of fluorine in water and use of nanomaterials in fluorine remediation in ground water

Fluorine, primarily seen in the form of fluoride, can pose several health hazards (Solanki *et al.,* 2021) when present in drinking water at elevated levels. Some of the important hazards of fluorine in Water include, dental fluorosis, characterized by discoloration and mottling of teeth. skeletal fluorosis, causing joint pain, stiffness, and changes in bone structure. Thyroid Issues, due to high fluoride levels interfering with thyroid function, and leading to hypothyroidism. In the worst cases, neurological effects and developmental issues in children.

4.5. Use of nanomaterials in fluorine remediation

Nanomaterials offer innovative solutions for the remediation of fluoride in groundwater (Dhillon *et al.,* 2022). Some notable approaches include the, adsorption by NPs of titanium dioxide, activated carbon, or metal oxides which are engineered at the nanoscale to enhance their adsorption capacity for fluoride ions. Modified surfaces or functionalizing nanoparticles with specific chemical groups, which can increase their affinity for fluoride. Membrane technologies or nanofiltration Membranes (Ayala *et al.,* 2018) can selectively remove fluoride ions from water, leveraging their small pore sizes and charge properties. Finally, Graphene Oxide is a material capable of selectively filtering out fluoride due to its high surface area and tunable properties

(Joya-Cárdenas *et al.*, 2022). Photocatalysis, is another technique, where in NPs are used to degrade organic fluoride compounds under UV light, converting them into less harmful substances. In Bioremediation, nano-enhanced bioreactors (Zhong *et al.*, 2024) are being used for incorporating nanoparticles to enhance the activity of microbial populations which can metabolize fluoride or facilitate its removal. Anoth promising area is the use of electrochemical Methods or using nanostructured electrodes (Bhattacharya *et al.*, 2017) which can improve the efficiency of electrochemical processes designed to remove fluoride from water. Thus, research in this area is going on to optimize these technologies for practical applications.

5. Nanomaterials in Solid Waste Management

Nanomaterials can help improve the sorting and recycling processes. For example, magnetic nanoparticles (Hernández-Saravia *et al.*, 2023) are used to recover valuable metals from electronic waste (e-waste), enabling more efficient recycling of materials like copper and gold. The integration of nanomaterials into plastics can improve recyclability (David *et al.*, 2020). Nanocatalysts are used to break down plastics more efficiently, enabling better recovery of materials from waste plastics. Nanocatalysts like platinum, palladium, and nickel nanoparticles are used to enhance the conversion of waste into energy, biofuel, (H. T. Nguyen *et al.*, 2024), and biodiesel. In processes like gasification and pyrolysis, nanomaterials can increase the yield of fuel gases (such as hydrogen and methane) from waste materials. Nanomaterials can enhance microbial digestion processes in anaerobic digestion systems, leading to more efficient production of biogas from organic waste (François *et al.*, 2023). Thus, nanomaterials can pave a better way fro the solid waste management effectively. As research continues, nanomaterials are expected to play a bigger role in creating sustainable waste management systems, improving recycling efficiency, and enhancing resource recovery from waste streams.

Conclusion and Future Directions:

Nanomaterials have emerged as promising tools for the sustainable remediation of air, water, soil, and fluoride pollution due to their unique properties, including high reactivity, large surface area, and ability to be engineered for specific interactions with pollutants. Their application spans a variety of methods, including adsorption, catalysis, and photodegradation, demonstrating effectiveness in breaking down or removing contaminants. However, while the results are encouraging, challenges remain regarding the long-term stability, environmental impact, and scalability of these technologies.

Future Directions

Multifunctional nanomaterials: The development of multifunctional nanomaterials that can tackle several contaminants at once could improve effciency and affordability. For instance, combining adsorptive and photocatalytic qualities may enable the removal and degradation of heavy metals and organic contaminants at the same time.

Biodegradable nanomaterials: The development of biodegradable nanomaterials should be the main goal of research to reduce environmental toxicity and persistence. This might assist in easing worries about possible nanomaterial buildup in ecosystems.
It is essential to move from lab research to practical applications. Pilot studies and field tests should be given top priority in future research to evaluate the viability and efficacy of nanomaterials.

Regulatory frameworks: It will be crucial to establish precise rules and legal frameworks for the application of nanomaterials in environmental remediation. This should include evaluating their effectiveness, safety, and influence on the environment.

At the same time, educating the public and stakeholders about the benefits and risks associated with nanomaterials' usage in remediation is needed for the acceptance and support for these technologies.

Interdisciplinary Research: Collaborative research between material scientists, environmental engineers, toxicologists, with policy makers is the need of the hour, which will ensure innovation and comprehensive approach to address the pollution control. By taking care of these crucial issues, the future of nanomaterials in sustainable remediation can be optimized, leading to effective solutions for air, water, soil, and fluoride pollution.

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CLIMATE CHANGE AND GLOBAL WARMING: CHALLENGES AND ADAPTATION STRATEGIES

Gayathri P. M* and Mahendra Kumar Yadav

School of Agriculture, RNB Global University, Bikaner, Rajasthan

*Corresponding author E-mail: gayathri.mohandas@rnbglobal.edu.in

Introduction:

Climate change describes the long-term modifications in Earth's typical weather patterns, including changes in temperature, rainfall, and other climatic factors, with global warming, caused by human actions, being a primary contributor. The release of greenhouse gases from fossil fuel use, deforestation, and industrial operations has enhanced the natural greenhouse effect, resulting in the warming of the Earth. It is important to understand the impacts of climate change and global warming, as these issues cross geographic regions and societal divides. The impacts stretch beyond environmental shifts, touching ecosystems, economies, and the welfare of current and future generations. A comprehensive understanding of these effects helps us prepare for challenges and implement strategies for mitigation and adaptation.

I. Effects of Climate Change

A. Environmental Consequences

1. Surge in Temperatures and Heat waves

With global temperatures on the rise because of climate change, heat waves are becoming more frequent and severe. Such heat waves pose substantial risks to natural ecosystems and human health. Higher temperatures can lead to heat-related illnesses, worsen air quality, and put a strain on energy supplies for cooling purposes

2. Thawing Ice Caps and Elevated Sea Levels

The melting of ice caps and glaciers, especially in the Polar Regions, contributes to the rise in sea levels. This leads to coastal erosion, increased vulnerability to storm surges, and threats to low-lying areas. Small island nations and coastal communities are particularly endangered, facing possible displacement and the loss of their means of living.

3. Changes in Precipitation Patterns and Severe Weather Events

Climate change drives shifts in precipitation patterns, altering how frequently and intensely rain falls. This can lead to prolonged drought conditions and heavier rainfall, which may result in flooding and landslides. Moreover, extreme weather events such as hurricanes, cyclones, and typhoons are becoming more frequent, causing significant damage and economic losses.

B. Effects on Ecosystems

1. Ecosystem Imbalance and Biodiversity Decline

The changing climate affects ecosystems by altering temperature and rainfall patterns, which in turn influences species distribution and behavior. This can lead to imbalances in predator-prey dynamics, shifts in plant communities, and diminished habitat suitability. As a result, biodiversity loss occurs, undermining the resilience and functionality of ecosystems.

2. Species Migration and Threat of Extinction

Species are increasingly challenged by changing environmental conditions that may surpass their tolerance limits. In response, some species migrate to find more suitable habitats, while others face the risk of extinction due to the rapid nature of these changes. Such shifts can cause ecological mismatches and impact ecosystems.

C. Societal Effects

1. Impacts on Food Security and Agricultural Systems

Climate change impacts agricultural productivity by modifying temperature and precipitation patterns, disrupting growing seasons, and raising the occurrence of pests and diseases. Together, these factors pose a significant threat to global food security, especially in areas where agriculture is vital for livelihoods and sustenance.

2. Issues Affecting Human Health

Increased temperatures and changing climate patterns have direct and indirect effects on human health. Heat-related illnesses, like heatstroke and heat exhaustion, become more frequent during heat waves. Additionally, temperature and precipitation shifts can affect the distribution of disease vectors, resulting in the spread of diseases such as malaria and dengue fever.

3. Climate-Induced Migration and Displacement

People residing in regions prone to sea-level rise, extreme weather events, and other climate-driven hazards are at risk of being displaced and forced to migrate. These climate refugees often encounter difficulties in finding new homes, gaining access to basic services, and adjusting to new communities, which could create social and political tensions.

II. Factors Driving Climate Change

A. Emissions of Greenhouse Gases

The leading cause of climate change is the emission of greenhouse gases, which trap heat in the atmosphere and contribute to global warming. These gases originate from various human actions and have a profound influence on Earth's climate system.

1. **Carbon Dioxide (CO2) Emissions from Fossil Fuel Combustion:** A major source of greenhouse gas emissions is the burning of fossil fuels like coal, oil, and natural gas to generate energy. These fuels are extensively used by industries, transportation systems, and

households. The combustion process releases carbon dioxide (CO_2) into the air, and CO_2 concentrations have surged since the Industrial Revolution, playing a significant role in the greenhouse effect and global warming.

2. **Methane Emissions Stemming from Livestock and Waste Disposal Sites:** Methane, another significant greenhouse gas, has a heat-trapping capacity many times greater than CO_2 over a short period. It is emitted from sources such as livestock digestion, manure management, and decomposing organic waste in landfills. Reducing methane emissions is critical for mitigating short-term climate effects.
3. **Nitrous Oxide Released Through Agricultural Practices:** Agricultural activities, including the use of synthetic fertilizers and certain land management methods, emit nitrous oxide (N_2O), a significant greenhouse gas that worsens global warming. Reducing N_2O emissions involves better fertilizer management, enhanced soil care, and more sustainable farming practices.

B. Land Clearing and Alterations in Land Use

1. **Decreased Carbon Sequestration Ability:** The process of deforestation entails clearing forests for various activities such as agriculture, logging, and urban development. Forests are vital for carbon sequestration, capturing CO_2 from the atmosphere and storing it in trees and soil. When forests are removed, the Earth's ability to absorb CO_2 diminishes, intensifying the greenhouse effect.
2. **Shifts in Regional Climate Condition:** Extensive deforestation and land-use changes can modify regional climates by disrupting natural weather patterns. Forests play a vital role in influencing both local and global precipitation, regulating temperatures, and shaping atmospheric circulation. When forests are lost, weather systems can shift, impacting rainfall distribution and potentially leading to droughts or floods in specific areas.
3. **Industrial Operations and Anthropogenic Actions:** Various industrial activities, such as manufacturing, mining, and cement production, generate greenhouse gases and pollutants. These emissions are linked to climate change and poor air quality. In addition, other human activities, including the release of fluorinated gases (e.g., hydrofluorocarbons and perfluorocarbons) in refrigeration and electronics manufacturing, also have considerable warming potential.

In summary, the drivers of climate change are diverse and originate from human actions that emit greenhouse gases and transform land use. Comprehending these causes is essential for crafting effective strategies to address climate change and implementing sustainable solutions in an ever-evolving world.

III. Mitigation Approaches

1. Adoption of Renewable Energy Sources

Adopting renewable energy sources is an essential strategy for reducing the impact of climate change. This transition involves leveraging sustainable and plentiful energy options such as solar, wind, hydroelectric, and geothermal power. Unlike fossil fuels, which generate greenhouse gas emissions when burned, these renewable alternatives provide cleaner energy solutions that significantly decrease carbon emissions. Integrating solar panels, wind turbines, and geothermal systems into energy networks paves the way for a more sustainable energy landscape.

2. Strategies for Enhancing Energy Efficiency and Conservation

Initiatives to boost energy efficiency and advocate for conservation are critical in the battle against climate change. By refining energy usage patterns in industries, households, and commercial sectors, we can significantly lower overall energy demand. This includes embracing advanced technologies that help minimize energy waste, such as energy-efficient appliances and lighting systems. Additionally, the focus on sustainable building designs promotes the construction of structures that make use of natural lighting, insulation, and ventilation to reduce energy needs.

1. Carbon Capture and Storage Techniques

In efforts to mitigate the ongoing emission of carbon dioxide (CO_2) from industrial processes, carbon capture and storage (CCS) technologies have received notable attention. These innovative techniques capture CO_2 emissions from power plants and industrial facilities prior to their release into the atmosphere. The captured CO_2 is then transported and stored in underground geological formations. By inhibiting a significant amount of CO_2 from entering the atmosphere, CCS technologies assist in reducing greenhouse gas concentrations.

2. Initiatives for Reforestation and Afforestation

Reforestation and afforestation are nature-focused strategies that aim to enhance carbon sequestration potential. Reforestation is the process of replanting trees in areas that have been deforested, whereas afforestation involves the establishment of forests in regions that were not previously forested. Both approaches promote carbon sequestration by allowing trees to absorb CO2 during photosynthesis. Additionally, forests contribute to biodiversity and help preserve ecological balance, further fostering a healthier planet.

3. Sustainable Transport and Urban Infrastructure

The heavy reliance of the transportation sector on fossil fuels creates a major challenge for climate change mitigation. Sustainable transportation and urban planning strategies provide a promising path forward. By promoting public transit options, such as buses and trains, we can decrease reliance on personal vehicles and the emissions they generate. Moreover, supporting electric vehicles (EVs) facilitates the shift towards cleaner transportation methods. In urban planning, developing walkable and bike-friendly areas minimizes the reliance on cars, which contributes to reduced emissions and better air quality. To sum up, the adoption of various mitigation strategies is vital for tackling the detrimental effects of climate change. Transitioning to renewable energy sources, boosting energy efficiency, utilizing carbon capture and storage (CCS) technologies, supporting reforestation and afforestation, and encouraging sustainable transportation and urban planning collectively lead us toward a more sustainable and resilient future. These approaches, coupled with global collaboration, present a promising path for mitigating the wide-ranging impacts of climate change.

IV. Climate Adaptation Measures

In light of the growing effects of climate change, implementing effective adaptation measures is critical. These measures focus on enhancing society's ability to cope with and adapt to the challenges that arise from a changing climate. This section investigates key adaptation strategies in different sectors.

1. Developing Climate-Resilient Infrastructure

Coastal regions are at high risk from rising sea levels and more intense storm events. To lessen these threats, it is crucial to develop strong coastal defenses and flood protection systems. These systems consist of various engineering strategies, such as seawalls, dikes, and levees that protect communities and valuable properties from the destructive impacts of flooding and coastal erosion.

2. Designing Resilient Buildings and Infrastructure

To effectively address climate change, innovative designs in architecture and infrastructure are essential for withstanding the challenges of a changing environment. Resilient buildings feature characteristics like raised foundations, durable materials, and efficient drainage systems, all aimed at mitigating flooding and other climate-related threats. Such designs not only improve the durability of structures but also lessen the impact of extreme weather conditions.

3. Advancing Agricultural Methods

Drought-Resilient Crops and Efficient Irrigation Techniques:

The agricultural sector is highly sensitive to changing climate conditions, necessitating adaptive measures to secure food supplies. Creating and growing drought-resistant crop varieties can help lessen the detrimental impacts of water shortages on agricultural yields. Furthermore, employing efficient irrigation systems, such as drip irrigation and precision watering, conserves water while ensuring crop productivity, especially during long dry spells.

4. Climate-Responsive Policies and Governance

Governments and policy-making bodies have a critical role in enhancing resilience to climate change. By considering climate factors in urban and regional planning, decision-makers can promote sustainable land use, manage resources effectively, and avoid developing in vulnerable areas. This proactive approach not only strengthens communities against climate-related risks but also supports long-term sustainability.

5. **Early Warning Mechanisms for Severe Weather Events**

Minimizing the impact of extreme weather events relies heavily on early warning systems. By employing advanced meteorological technologies and data, these systems provide timely alerts to communities, allowing them to take preventive actions and evacuate if necessary. Such mechanisms are vital for saving lives and protecting property, forming an essential part of climate adaptation strategies.

6. **Community Involvement and Awareness**

Creating awareness and fostering a culture of readiness in communities is vital for effective climate adaptation. Educating individuals about the dangers of climate change and the adaptive measures they can take empowers them to make knowledgeable decisions. Through workshops, educational initiatives, and public outreach, communities can gain the skills and understanding needed to contribute to climate resilience actively. In essence, adaptation measures encompass various strategies, ranging from engineering solutions to informed policies and community engagement. By embracing these strategies, societies can tackle the challenges posed by climate change and work toward a more resilient and sustainable future.

Conclusion:

In this chapter, we explored the complex relationship between climate change and global warming, revealing a wide array of effects on both the natural environment and human societies. Rising temperatures, melting ice caps, altered precipitation patterns, and extreme weather events are clear indicators of our shifting climate. Ecosystem disruptions and the imminent threat of biodiversity loss pose serious environmental challenges, with the potential impacts on food security, human health, and displacement emphasizing the urgent need for societal intervention. Addressing climate change necessitates a collaborative global response that transcends borders and political divisions, as its impacts affect economies, cultures, and ecosystems worldwide. Now is the time for unified action, moving beyond isolated efforts to create partnerships that leverage the collective knowledge and resources of nations, industries, and individuals. As we confront these profound challenges, we must prioritize both mitigation and adaptation strategies. Mitigation efforts, such as transitioning to renewable energy, enhancing energy efficiency, and promoting reforestation, can help prevent further environmental degradation. At the same time, adaptation measures focused on building climate-resilient infrastructure, improving agricultural practices, and implementing climate-informed policies are crucial for successfully navigating the changes already in motion.

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About Editors

Prof. Dr. Yashodhara Shrikant Varale is presently working as I/C Principal, Dr. Ambedkar College of Commerce and Economics, Wadala 400031, Mumbai. She has been awarded with Ph. D. in 2003 from Dr. Babasaheb Ambedkar Marathwada University, Aurangabad, Maharashtra. Sha has 17 years of teaching and 19 years of research experience. She has published more than 50 research articles in various national and international reputed journals. She has received many National Level Award for her outstanding performance and contribution in the field of teaching, research and social activity. She is working as member of advisory board, reviewer board, editorial boards of many journals. Dr. Varale is Lifetime member of Indian Social Science and many other associations in the field of social science.

Dr. Gangotri Sunil Nirbhavane is an Associate Professor in Environmental Studies at Dr. Ambedkar College of Commerce & Economics, Wadala, Mumbai, where she has been teaching since 2009. With over 16 years of experience, she completed her Ph.D. in 2017 on groundwater quality in the Ambarnath MIDC area, Thane. Her research interests encompass water pollution, water quality, electronic waste, plastic waste, and urban environmental issues. Dr. Nirbhavane is frequently invited as a resource person and guest lecturer in Environmental Science across colleges in Mumbai and Aurangabad. She has served as a judge at events such as the National Youth Festival by Praja Foundation and the V.K. Kotnis Inter School Elocution Competition. Dr. Nirbhavane has published 29 research papers, six book chapters, and 19 Marathi articles on environmental issues. She has also received appreciation certificates from several organizations, including the Antarang Foundation and Kotak Education Foundation.

Dr. Amol S. Shyamkuwar is currently serving as an Assistant Professor in the Department of Microbiology at S.S. Jaiswal College in Arjuni/Mor, District – Gondia. He earned his Master's degree in Microbiology in 2005 and obtained his Doctorate in Medical Microbiology from RTM Nagpur University, Nagpur in 2014. In 2012, he also qualified the NET (LS) examination. With a total of 12 years of teaching experience, he has authored multiple research papers published in esteemed journals in Medical Microbiology and Environmental Field.

Dr. Nandita Jena with M.Sc., M.Phill., Ph.D, is presently working as an Associate Professor in the Department of Crop Physiology at Faculty of Agricultural Sciences, SOA DU, Bhubaneswar. She has 30 years of teaching and research experience of UG, PG and PhD level. She has completed her Ph.D. (Botany) and ICAR NET in Plant Physiology in 1997. Dr. Jena has published 20 research papers, 23 conference presented papers, 12 book chapters, 2 patents and many popular articles on her credit. She has attended hundreds of national and international seminars/conferences/webinars and also the life member of many associations like ISCA, OES etc. She has successfully completed ARPIT Refreshers Course on "Advances in Agricultural Engineering certificate course", workshops and 17 FDPs. Dr. Jena has received best participant Award in FDP and Best Oral Presentation Award in many conferences. She has guided more than 25 M.Sc. students. Currently two are pursuing doctoral study including other M.Sc. students under her supervision.

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