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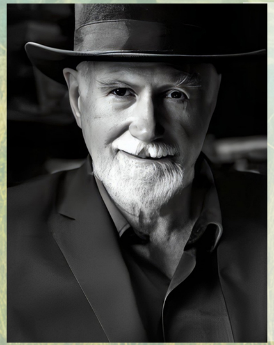

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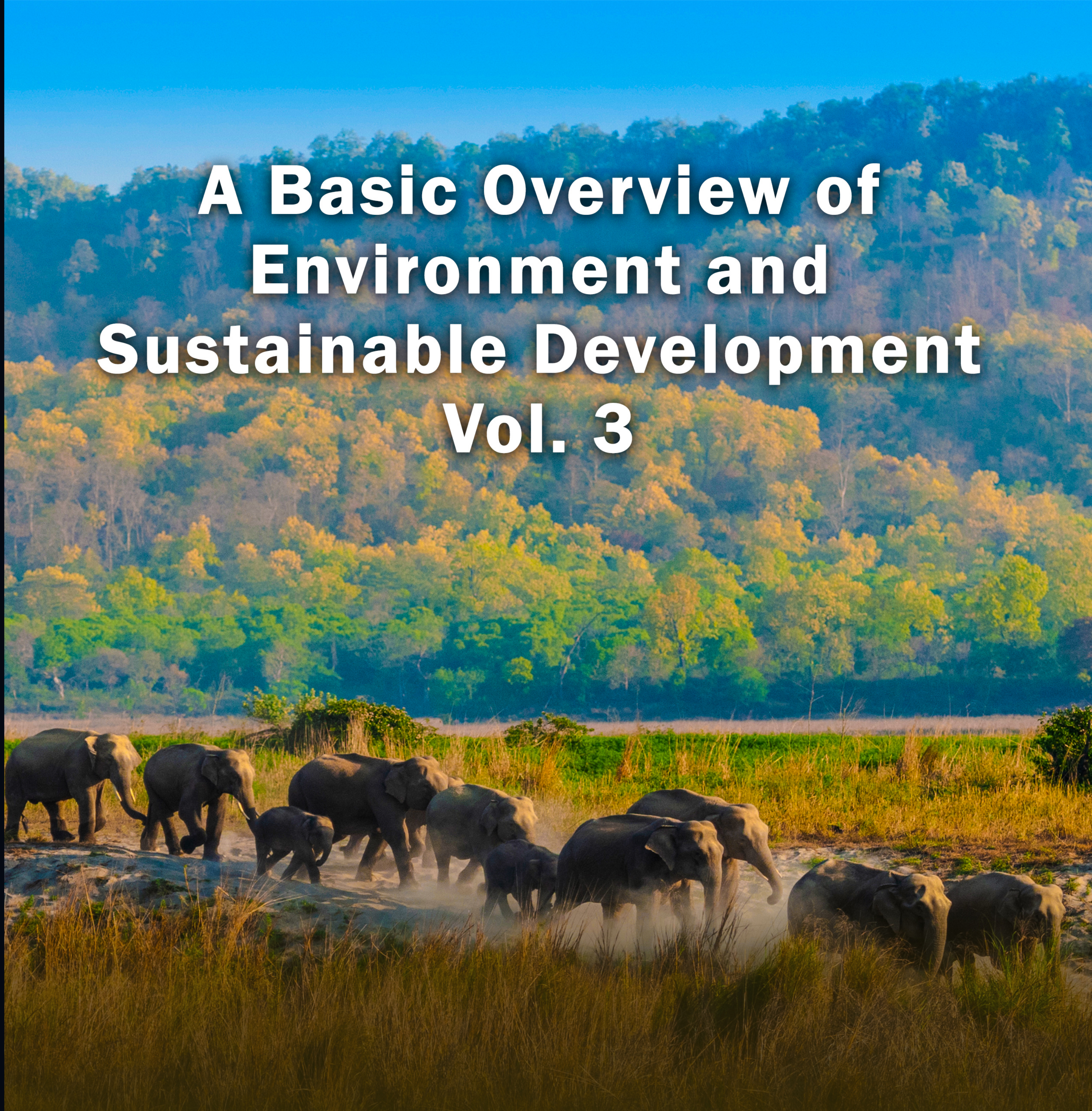

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Editors:

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PREFACE

The challenges we face today highlight the need to understand the relationship between protecting the environment and pursuing sustainable development. This third volume of "Environment and Sustainable Development" arrives at a crucial moment when rethinking how we grow and progress is essential. Rapid technological advancements, urban expansion, and rising populations have intensified the pressure on our planet's resources. We must find ways to advance that do not come at the cost of the natural world. In this volume, we place greater emphasis on practical approaches and real-world strategies for achieving a balance between human needs and environmental care. Although the issues of climate change, pollution, and biodiversity loss remain urgent, this book sheds light on successful efforts and solutions that offer hope. By presenting these examples, we show that sustainable development is not only possible but can be incorporated into everyday life across different sectors. Our aim goes beyond simply providing information; we seek to inspire readers to think critically and take action. Sustainable development is not a distant or optional goal—it is essential for a future where economic growth, social fairness, and environmental health coexist. This approach ensures that future generations will inherit a world worth living in.

We are deeply grateful to the contributors whose expertise and dedication have shaped this volume. Their efforts have made it a valuable resource that is both practical and insightful. We hope this book reaches a wide audience, from students to policymakers, and spurs actions that lead to meaningful change.

The cover image features a group of elephants in Jim Corbett National Park, India. This photograph, captured by professional wildlife photographer and Nikon expert Ramesh Karmakar, who was a student of Dr. Tanmay Sanyal, holds the exclusive copyright. Its use as our book cover is made possible through his permission. It serves as a reminder that the steps we take today will shape the future we leave behind. Let this volume be a guide and an invitation to work together for a sustainable and balanced world.

Dr. Nithar Ranjan Madhu,
Dr. Tanmay Sanyal,
Dr. Koushik Sen,
Professor Biswajit (Bob) Ganguly
and Professor Roger I.C. Hansell

Contents

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Chapter- 1

Sustainable Management of Organic Wastes to Enhance Soil Health via Vermicomposting

Sruti Karmakar*, Rakesh Acharya, Debnarayan Roy and Koushik Sen

Keywords: Organic waste, Earthworm, Vermicomposting, Soil health, Soil productivity

Abstract:

Vermicomposting is the process of converting large amounts of organic waste into organic fertilizer using earthworms. This straightforward biotechnological method utilizes specific species of earthworms to transform waste into a superior end product. Vermicomposting is an efficient waste management technique, as it produces high-quality manure quickly and yields a nutritionally rich and biologically active product at a reasonable cost. The resulting vermicompost is a highly nutritive, humus-like organic fertilizer rich in macronutrients and micronutrients. It plays a crucial role in enhancing the growth and yield of crops. The effective utilization of waste materials through vermicomposting not only supports sustainable nutrient management and the maintenance of soil health in agricultural soils but also helps in reducing environmental pollution caused by waste. This review aims to raise awareness about generating value from waste through vermicomposting.

Introduction:

Waste is defined as an unwanted material or substance that is deliberately discarded for disposal. Since the Industrial Revolution, the generation of waste has increased rapidly, exacerbated by the ever-growing human population, which has contributed to additional hazards and highlighted waste as a significant factor in environmental health (Siddiqua et al., 2022; Mohan and Joseph, 2021; Thakur et al., 2021; Das et al., 2022; Erfani et al., 2024; Hemalatha et al., 2024). With rising populations and improving living standards, the demand for our environment has increased, leading to the depletion of more raw materials, including non-renewable resources. As a result, more waste is being produced today, and unless it is

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managed properly, it will lead to increased pollution (Talashilkar et al., 1999; Kaza et al., 2018; Bandyopadhyay et al., 2023).

Scientists observed that the problems associated with various types of man-made waste are gradually increasing due to population growth, rapid industrialization and urbanization trends (Bharadwaj, 2010). Waste can be categorized into different types, such as solid, liquid, and gas, each requiring careful management, with solid waste management alone covering a vast field. Solid wastes are generated from various sources, including institutions, agriculture, and industry. In cities of developing countries, inadequate arrangements for solid waste collection and disposal contribute to environmental degradation. Local agencies often find themselves unable to manage the increasing volumes of waste, leading to uncollected waste accumulating on roadsides, street corners, or other open spaces in cities, thereby posing health risks to the public (Kaseva and Mbuligwe, 2005; Rathi, 2006; Imam et al., 2008; Thirunavukkarasu et al., 2023).

Improper disposal of large amounts of waste in developing urban areas poses threats to air, water, land, vegetation, wildlife, and humans (Awomeso et al., 2010). Inadequate disposal and management of sewage, garbage, and other unwanted substances often spread illnesses and epidemic diseases. The continuously growing human population and rising income levels contribute to increased demand and production of goods, leading to the discharge of more waste into the environment (Varian, 2010; Blanchard, 2009; Kaza et al., 2018; Thirunavukkarasu et al., 2023). Household organic waste contributes significantly to Municipal or Corporation garbage, which has become a pressing environmental issue today. Composting offers a solution by converting such waste into valuable resources. This environmentally friendly technique does not cause any pollution (Gajalakshmi et al., 2002; Bansal and Kapoor, 2000; Quadar et al., 2022; Tawarah et al., 2024).

The preparation of vermicompost is both an efficient and easily adaptable method for compost production. This system not only effectively decomposes large quantities of organic waste but also helps maintain a higher nutrient status in the composted material (Bajsa et al., 2004; Gopal et al., 2017; Thirunavukkarasu et al., 2023). Consequently, vermicomposting is recognized as a more sustainable technique for organic waste disposal through vermiculture, the science of breeding and raising earthworms. Introduced in the Philippines in the late 1970s, vermicomposting gained popularity throughout the 1980s (Guerrero, 1979; Guerrero, 2009).

Vermicomposts are noted for their exceptional biological properties, supporting microbial populations that are significantly larger and more diverse than those found in conventional thermophilic composts (Edwards, 1998). This composting process is non-toxic, requires low energy input, and produces a recycled bio-organic product. Due to the absence of toxic enzymes, vermicompost is eco-friendly and has a beneficial impact on the biochemical activities of the soil (Ali and Jahan, 2001; Ghoshal, 2017; Bhat et al., 2017). It also improves soil quality, fertility and mineral content, enhancing soil aeration, texture, and tilth while reducing soil compaction. Moreover, vermicomposting increases the soil's water retention capacity due to its high organic matter content and promotes better root growth and nutrient absorption (Nourbakhsh, 2007; Quadar et al., 2022; Tawarah et al., 2024).

This study aims to provide an overview of the potential of vermicomposting for eco-friendly organic waste management. In addition to a general overview, this work specifically explores the potential of (i) vermicomposting in organic waste management, (ii) the effects of vermicompost on soil health, (iii) the role of vermicompost in crop yield, and (iv) the use of vermicomposting to reduce the toxicity of raw materials. Therefore, this work seeks to present a comprehensive picture of vermicomposting and its role in soil health management.

Utility of vermitechnology in organic waste management

Vermicomposting is an efficient biotechnological method for composting in which specific species of earthworms are employed to convert organic waste into a superior end product (Alshehrei and Ameen, 2021; Thirunavukkarasu et al., 2023; Hemalatha et al., 2024). According to Gandhi et al. (1997), vermicomposting differs from traditional composting methods. It is a mesophilic process that utilizes microorganisms and earthworms, which are active at temperatures between 10°C and 32°C (not the ambient temperature, but the temperature within the pile of moist organic material). This process is faster than regular composting, and as the material passes through the earthworm's digestive system, it undergoes significant transformation. The resulting earthworm castings, or worm manure, are enriched with beneficial microbes and plant growth regulators and possess pest repellent properties.

Earthworms are known to consume and break down a wide range of organic residues, including agricultural, animal, industrial, and domestic wastes, sewage sludge, and crop residues. Solid waste, including wastewater sludge from the paper pulp and cardboard industries, breweries and distilleries, sericulture industry, vegetable oil factories, potato and corn chip manufacturing industries, sugarcane industry, aromatic oil extraction industries, and logging and carpentry industries, provides excellent feed material for vermicomposting by earthworms (Gajalakshmi et al., 2002; Bansal and Kapoor, 2000; Ndegwa et al., 2000; Singh and Suthar, 2012; Lakshmi and Vijayalakshmi, 2000).

As Dominguez (2004) describes, vermicomposting involves earthworms processing large amounts of organic residues into organic manures. It has been demonstrated to be a cost-effective technique due to its low expenses. The process involves the bio-oxidation and stabilization of organic materials through the combined action of earthworms and microorganisms. Microbes are responsible for the biochemical degradation of organic matter, while earthworms play a crucial role in conditioning the substrate and altering its biological activity. Dominguez's study highlights that earthworms can process sewage sludge, soils from wastewater, materials from breweries, paper wastes, urban residues, and animal wastes.

Palaniappan and Annadurai (2008) reported that vermiculture biotechnology involves using earthworms as versatile natural bioreactors to effectively recycle non-toxic organic wastes, leading to soil improvement and sustainable agriculture. This technology is currently being utilized to establish cost-effective units for treating various non-toxic organic solid and liquid wastes from cities, dairies, sugar and distillery units, pulp and paper mills, tanneries, fermentation industries, and food processing units (Tawarah et al., 2024; Thirunavukkarasu et al., 2023).

Aira et al. (2002) noted that vermicomposting involves the stabilization of organic material through the combined action of earthworms and microorganisms. In this process, earthworms are essential drivers, conditioning the substrate and modifying its biological activity, while microbes are responsible for the biochemical degradation of organic matter. Epigeic earthworms have been utilized for organic waste management due to their effectiveness in accelerating the composting process (Suthar, 2006; Benitez et al., 2005; Garg and Kaushik, 2004; Yadav and Garg, 2011; Bhat et al., 2017).

Ndegwa and Thompson (2001) explained that during vermicomposting, nutrients are released and converted into forms that are soluble and available to plants. Elvira et al. (1996) observed that the earthworm *Eisenia andrei* effectively converted paper-pulp mill sludge mixed with primary sludge into vermicompost. Suthar (2008) studied the recycling of post-harvest crop residues and cattle shed manure through vermicomposting using the epigeic earthworm *Eudrilus eugeniae*, which significantly accelerated the composting process and enhanced the availability of nutrients in the vermicompost.

When combined with industrial effluents, Hema and Rajkumar (2012) found that vegetable wastes could be effectively degraded by earthworms, increasing nutrient content and worm populations in the order of dairy, distillery, and water. They concluded that vermicomposting is an appropriate technique for efficiently recycling and disposing of non-toxic solid and liquid wastes. According to Prabha et al. (2005), vermi-technology is a significant aspect of biotechnology, utilizing earthworms to process various organic wastes into valuable resources. Lal et al. (2003) reported that vermicomposting helps process waste and simultaneously produces manure and protein. Thus, vermi-technology can be effectively used to clean the environment by using wastes as raw materials to transition from polluted, costly chemical farming to sustainable agriculture.

Role of vermicompost in improving soil health and productivity

Vermicompost, also known as vermicast, is a type of organic compost that is rich in essential nutrients like nitrogen, phosphorus, and potassium (NPK), as well as various micronutrients necessary for plant growth (Bhardwaj et al., 2023; Tawarah et al., 2024). This compost has become increasingly popular among organic farmers because it promotes faster and more vigorous plant growth without the need for chemical fertilizers. While thermophilic composting has long been known for its ability to improve soil fertility (Zaller and Kopke, 2004; Mane and Raskar, 2012; Santra et al., 2015) and suppress plant diseases (Hoitink and Fahy, 1986), research is showing that vermicompost can also provide these benefits (Edwards and Burrows, 1988; Edwards et al., 2004).

Vermicompost is a finely textured, peat-like material with high porosity, good aeration, excellent drainage, and strong water-holding capacities. It is produced through the breakdown of organic waste by earthworms and microorganisms, without the material passing through a thermophilic (heat-producing) stage (Domínguez, 2004; Quadar et al., 2022; Tawarah et al., 2024). This process results in composts rich in nutrients like nitrates, calcium, phosphorus, and potassium, which plants easily absorb. Vermicompost also provides numerous microsites for microbial activity and has large surface areas that help retain nutrients (Edwards and Burrows, 1988).

What makes vermicompost stand out is its outstanding biological properties. It supports a larger and more diverse microbial population than conventional thermophilic composts (Edwards, 1998). Vermicompost is produced through a non-thermophilic process where organic matter is broken down by the interactions between earthworms and microorganisms under aerobic (oxygen-rich) conditions (Bhardwaj et al., 2023). This type of compost is valuable because it releases nutrients at a balanced rate, providing essential elements like nitrogen, potassium, calcium, magnesium, and phosphorus, which plants can easily take up (Edwards, 1998; Edwards and Fletcher, 1988).

Most studies have focused on the impact of solid compost and vermicompost on soil fertility and plant disease suppression (Addabdo, 1995; Edwards, 1998; Dominguez, 2004), with less research on their use as liquid extracts. Organic manures, including vermicompost, have been shown to improve soil microbial properties, which can lead to high and sustained crop yields when used in combination with balanced NPK fertilization (Makinde et al., 2001; Bayu et al., 2006; Bhat et al., 2017). Nutrients in organic manures are released slowly and remain in the soil for longer periods, ensuring a prolonged residual effect (Sharma and Mitra, 1991).

Adding organic amendments like compost or vermicompost to soil can enhance its buffering capacity and significantly influence its physicochemical behavior, thanks to the humic acid content and its associated charge development and acid–base properties (Gondar et al., 2005; Campitelli et al., 2006; Benitz et al., 2005). Applying vermicompost improves soil health by enhancing water-holding capacity, soil structure, and fertility (Jeyabal and Kuppuswamy, 2001; Chaoui et al., 2003; Tawarah et al., 2024).

Vermicompost is a nutrient-rich plant food that contains NPK, micronutrients, and beneficial soil microbes like nitrogen-fixing bacteria and mycorrhizal fungi. It includes growth-promoting hormones like auxins and gibberellins, which boost plant development (Tomati et al., 1985). The mycorrhizal fungi encouraged by earthworms help increase the solubilization of mineral phosphate, enhancing phosphorus availability. Vermicompost also contains enzymes such as amylase, lipase, cellulase, and chitinase, which continue to break down organic matter in the soil, releasing nutrients that plants can easily absorb (Chaoui et al., 2003; Quadar et al., 2022; Bhardwaj et al., 2023).

Rich in microbial diversity, especially fungi, bacteria, and actinomycetes (Brown, 1995; Chaoui et al., 2003; Singh, 2009; Lim et al., 2016), vermicompost fosters a thriving soil ecosystem. Studies have shown that vermicompost contains a high concentration of beneficial bacteria, including Actinomycetes, Azotobacter, Rhizobium, Nitrobacter, and phosphate-solubilizing bacteria (Suhane, 2007).

Incorporating vermicompost into soil management practices can significantly improve soil health, enhance plant growth, and promote sustainable agriculture.

Application of vermicompost in improving crop yield and quality

Vermicompost significantly enhances the growth and yield of a variety of crops, including field crops, vegetables, flowers, and fruits. For instance, the application of vermicompost led to a notable increase in germination rates of mung bean (Vigna radiata) to 93%, compared to 84% with the control. Furthermore, vermicompost application resulted in superior growth and yield of mung bean. Similarly, in a pot experiment, cowpea (Vigna unguiculata) showed higher fresh and dry matter yields when soil was amended with vermicompost rather than biodigested slurry (Karmegam et al., 1999; Karmegam and Daniel, 2000).

Desai et al. (1999) assessed the efficiency of vermicompost in field studies, finding that its application, combined with fertilizer nitrogen, resulted in higher dry matter (16.2 g per plant) and grain yield (3.6 t ha^-1) of wheat (Triticum aestivum). Additionally, it improved the dry matter yield (0.66 g per plant) of coriander (Coriandrum sativum) in a sequential cropping system. Positive outcomes were also reported with vermicompost application for other field crops such as sorghum (*Sorghum bicolor*) (Patil and Sheelavantar, 2000; Tawarah et al., 2024) and sunflower (Helianthus annuus) (Devi and Agarwal, 1998). Vadiraj et al. (1998) noted that vermicompost provided herbage yields of coriander cultivars comparable to those obtained with chemical fertilizers.

In ornamental horticulture, vermicompost enhanced the growth of Chrysanthemum chinensis, with the highest fresh weight of flowers achieved using 10 t ha^-1 of vermicompost combined with 50% of the recommended dose of NPK fertilizer. The maximum number of flowers per plant (26), flower diameter (6 cm), and yield (0.5 t ha^-1) were observed with this treatment. The vase life of flowers (11 days) was extended with a combination of 15 t ha^-1 of vermicompost and 50% of the recommended NPK fertilizer (Nethra et al., 1999; Bhardwaj et al., 2023).

Vermicompost is a highly nutritious organic manure, rich in humus and essential nutrients such as nitrogen (2-3%), phosphorus (1.55-2.25%), and potassium (1.85-2.25%), along with micronutrients and beneficial soil microbes, including nitrogen-fixing bacteria and mycorrhizal fungi. It has been scientifically validated as an effective plant growth promoter (Tiwary et al., 1989; Binet et al., 1998; Chaoui et al., 2003). Its high porosity, aeration, drainage, and water-holding capacity make it an excellent medium for plant growth. Vermicompost contains plant-available nutrients and enhances their retention over extended periods. Importantly, it increases plants' biological resistance to pests and diseases through repelling or suppressing pathogens (Anonymous, 2001; Rodriguez et al., 2000; Edwards and Arancon, 2004).

Murarkar et al. (1998) investigated the effects of vermicompost on mulberry (Morus sp.) leaf yield, finding that a combination of full-dose NPK fertilizers and vermicompost, along with a half dose of farmyard manure, significantly improved the number of branches, plant height, number of leaves per plant, and leaf yield per plant. Tomar et al. (1998) reported that brinjal plants grown with vermicompost had higher yields (97.0 g per plant) compared to those grown with other treatments. Similarly, carrots grown with vermicompost yielded 94.9 g per pot, compared to 29.9 g and 36.0 g with unamended soil and farmyard manure, respectively.

Vermicompost enhances soil properties, increases crop yields, and significantly improves the growth of plants such as Pisum sativum compared to pit compost and garden soil (Khan and Ishaq, 2011; Lim et al., 2016). George and Pillai (2000) found that applying vermicompost, alone or in combination with chemical fertilizers, stimulated crop growth and reduced the amount of recommended NPK by up to 25% in Guinea grass grown as an intercrop in coconut. Increased crop yields and quality have been frequently observed in plants grown with earthworm castings, and organic produce is often noted for its superior nutritional quality, taste, and storage life (Palaniappan and Annadurai, 2008; Lim et al., 2016; Bhardwaj et al., 2023).

Vermicompost, containing antibiotics and actinomycetes, enhances plants' biological resistance to pests and diseases, leading to reduced pesticide use (Suhane et al., 2008; Quadar et al., 2022). Athani and Hulamani (2000) reported that bananas treated with vermicompost and NPK fertilizers had extended shelf life, with plants receiving 125,000 earthworms ha^-1 showing the longest shelf life. Lazcano et al. (2011) demonstrated that both vermicompost and manure significantly increased plant growth and marketable yield, highlighting the positive effects of organic fertilizers on crop yield and quality.

Using vermicomposting to decrease the toxicity of raw materials

Vermicomposting is an advanced biotechnological process where earthworms convert various organic wastes into a humus-like substance known as vermicompost. Earthworms can decompose a wide range of organic materials, including sewage sludge, animal waste, agricultural residues, household waste, and industrial by-products. Sewage sludge, in particular, is used extensively in agriculture worldwide, either in its raw form or as processed products (Buta et al., 2021). Sewage sludge contains valuable macro- and micronutrients as well as organic compounds essential for plant growth, enhancing crop production and soil quality (Tu et al., 2012; Latare et al., 2014; Bourioug et al., 2014). However, it also harbors hazardous contaminants like Potentially Toxic Elements (PTEs), including Pb, Cr, Cd, Ni, As, Zn, and Cu, which can adversely affect the environment (Villar et al., 2016; Lv et al., 2016). These contaminants pose significant environmental health risks due to their toxicity and potential for bioaccumulation in the food chain.

Vermicomposting involves a synergistic action between earthworms and microorganisms that bio-oxidize and stabilize organic materials. Microorganisms primarily handle the biochemical breakdown of organic waste, while earthworms assist in this process. Vermicomposting can also act as an environmental sink for PTEs, converting most organic matter into nutrient-rich products containing nitrogen, phosphorus, and potassium (NPK) and humic substances (Lv et al., 2016; Dume et al., 2022). Additionally, earthworms accumulate metals in their tissues, thereby reducing the concentration of PTEs in the final vermicompost product (Sizmur et al., 2009; Li et al., 2010).

The pH of vermicompost can vary depending on the raw materials used. For instance, vermicompost from sewage sludge typically has a pH of 7.2 (Masciandaro et al., 2000), while vermicompost from pig manure ranges from 5.3 (Atiyeh et al., 2002a) to 5.7 (Atiyeh et al., 2000). In contrast, vermicompost derived from sheep manure has a pH of 8.6 (Gutiérrez-Miceli et al., 2008). This variation in pH is linked to the characteristics of the raw materials used in vermicomposting. Vermi-composting of sheep manure for 60 days has been shown to eliminate pathogens such as E. coli, Shigella spp., Salmonella spp., and total coliforms compared to untreated raw sheep manure (Gutiérrez-Miceli et al., 2008). This reduction in pathogens is likely due to the antibacterial properties of vermicompost, which are attributed to the hemolytic activity of earthworms (Sinha et al., 2002).

Aira et al. (2012) studied the impact of the earthworm species *Eisenia andrei* on pathogen reduction during cow dung vermicomposting in an industrial-scale continuous feeding vermi-reactor. They found that while *Eisenia andrei* did not significantly reduce Enterobacteria, total coliforms, or Clostridium, it did lower Escherichia coli, fecal coliforms, and fecal enterococci levels. The effectiveness of pathogen reduction can vary depending on the earthworm species used (Aira et al., 2012; Fernando et al., 2021).

Research suggests that the decrease in total coliforms during vermicomposting may be related to the natural characteristics of earthworms, their digestive capabilities, and the enzymatic digestion performed by bacteria in their gut (Monroy et al., 2008; Monroy et al., 2009; Edwards et al., 2011). Earthworm species such as *Eisenia fetida*, *Eisenia andrei*, *Eudrilus eugeniae*, and *Lumbricus rubellus* have effectively reduced total coliform counts (Monroy et al., 2008). Esmaeili et al. (2020) demonstrated that combining composting with vermicomposting using pistachio waste and cow dung produced a superior end product with a low C

ratio, decreased total organic carbon and increased total nitrogen and phosphorus content.

Heavy metal contamination from agricultural and industrial activities is a significant concern, with lead (Pb) being particularly problematic. However, animal manure and crop residues have been identified as effective organic adsorbents for heavy metals (Wang et al., 2015; Wnetrzak et al., 2014). Zhang et al. (2020) found that biochar derived from cow manure-based vermicompost could effectively adsorb Pb^{2+} from solutions. Produced through pyrolysis at temperatures of 350°C and 700°C, this biochar has an acidic pH (2.0 and 3.0) and rich mineral content, which facilitates the rapid removal of Pb^{2+}. Thus, biochar from cow manure vermicompost offers an affordable solution for heavy metal removal from soil and water (Fernando et al., 2021).

Figure 1. Raw material for vermicomposting.

Figure 2. Mature vermicompost.

Figure 3(a&b). Earthworm faeces.

Figure 4(a&b). Earthworm for vermicompost production.

Conclusion and Future Direction:

Organic waste management is a critical challenge due to waste accumulation's environmental and health impacts. Vermi-composting, utilizing earthworms to convert organic waste into nutrient-rich compost, offers an effective solution. This process manages waste and improves soil health and fertility, thereby enhancing crop production. The vermicompost's physical, chemical, and biological properties vary, affecting plant growth and soil quality.

Looking ahead, integrating nanotechnology and artificial intelligence (AI) into vermicomposting presents promising advancements. Nano-technology can enhance the efficiency of composting by improving nutrient availability and contaminant breakdown. AI can optimize the process through real-time monitoring and data analysis, enabling precise control over composting conditions. Combining these technologies with traditional vermicomposting methods could lead to more effective waste management, better soil health, and improved agricultural outcomes, addressing the pressing challenges of organic waste management in a sustainable manner.

Conflict of interest:

None

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Chapter- 2

Exploring the Riches of *Rauvolfia serpentina*: Botany, Pharmacology, and Conservation Perspectives

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Keywords: *Rauvolfia serpentina*, Sarpagandha, Palynology, Pharmaceutical, Ethnobotanical, Conservation, Nanobiotechnology, Alkaloids, Reserpine, Serpentina, Traditional medicine

Abstract:

Rauvolfia serpentina (L). Benth. ex-Kurz, commonly known as Sarpagandha, is a vital medicinal plant native to the Indian subcontinent and Southeast Asian countries. This comprehensive review explores the botanical description, palynology, pharmaceutical properties, ethnobotanical practices, applications in nanobiotechnology, *in vitro* propagation, and bioinformatics associated with this plant. Belonging to the Apocynaceae family, *R. serpentine faces endangerment due to the overexploitation of* its bioactive constituents, which prompts the need for sustainable conservation strategies. The Apocynaceae family, distributed worldwide, encompasses approximately 400 genera and 5000 species. Among the six Indian species of the *Rauvolfia* genus, *R. serpentina* and *R. tetraphylla* are particularly valued for their medicinal properties, with R. *serpentina* facing extinction and listed under CITES Appendix II. This study delves into the phytochemical composition of *R. serpentina*, emphasizing the therapeutic virtues of its alkaloids, including the renowned reserpine, ajmaline, ajmalicine, serpentina, rescinnamine, deserpidine and yohimbine. These alkaloids contribute to the plant's efficacy in treating hypertension, mental disorders, and snake bites. Pollen morphology, ayurvedic pharmacodynamics, and ethnoveterinary practices are also discussed, highlighting the plant's diverse applications in traditional medicine. The mineral composition of *R. serpentina* suggests potential therapeutic roles in managing diabetes and aiding blood coagulation. Recent advancements in *in vitro* propagation techniques are explored to address challenges in commercial cultivation. Furthermore, the plant's role in synthesizing nanoparticles and the existence of SerpentinaDB, a structured compilation of plant-derived molecules from *R. serpentina*, provide avenues for future research and development. The present sequel has been emphasized and counteracted with the multifaceted exploration of R. serpentine with its significance as a traditional medicine, pharmaceuticals, and conservation efforts among the society at large. Because of overharvesting and habitat destruction, the *Rauvolfia* genus of medicinal plants is experiencing a decline in population, making conservation efforts essential. Protecting habitat and using sustainable farming methods are crucial to maintaining these priceless species and their ecological significance.

Abbreviations used:

AgNPs: Silver Nanoparticles; CITES: Convention on International Trade in Endangered Species of Wild Fauna and Flora; NPACT: Naturally Occurring Plant-based Anti-cancer Compound-Activity; PDMs: Plant-Derived Molecule

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Rauvolfia serpentina, also known as **Sarpagandha** in Hindi, is a remarkable **Ayurvedic herb** with a rich history of use. Let's explore its fascinating properties:

Botanical Description:

Scientific Name: *Rauvolfia serpentina*

Common Names:

English: Indian Snake Wood, Serpentina Wood

Hindi: Sarpagandha, Chandrabagha, Chota chand

Sanskrit: Sarpagandha, Chandarmar

Habitat: Native to India, Burma, Sri Lanka, China, and Pakistan, it thrives in moist forests.

Plant Features:

An evergreen perennial undershrub.

Grows up to around 2 feet in height.

Oval leaves in whorls of 3, with paler green below and dark green above.

Irregular corymbose white flowers with a violet tinge.

Oval fleshy fruits are around 1 cm long, turning shiny purple-black when ripe.

Milky sap.

Medicinal Parts: The roots of *Rauvolfia serpentina* are used for their medicinal properties.

Medicinal Uses:

Antihypertensive: Used for managing high blood pressure (hypertension).

Sedative and Antianxiety: Helps calm the central nervous system, reducing anxiety and irritability.

Antipsychotic: Used in mental disorders alongside Jatamansi (Spikenard).

Hypnotic: Aids in treating insomnia (sleeplessness).

Rauvolfia serpentina (L). Benth. ex-Kurz., also known as Sarpagandha, is an essential medicinal plant native to the Indian subcontinent and South East Asian countries, generally in the region having annual rainfall of 200 to 250 cm, up to an altitude of 1000 m and in deep fertile soil rich in organic matter (Dey and De, 2010). The plant is distributed worldwide in the region of the Himalayas, the Indian peninsula, Burma, Indonesia, and Sri Lanka belongs to the Apocynaceae family and is commonly known as Sarpagandha, Chandrabagha, Snake root plant, Chotachand, Chandrika, and Harkaya (Ojha and Mishra, 1985). The plant has several characteristics: tuberous roots with pale brown cork; Leaves in whorls of three, with dark green color above and pale green color below; white, pinkish, or red flowers (Figure 1) occurring in whorls; Small, oval fruits (Deshmukh et al., 2012).

Certain plants' roots, leaves, and juice contain various secondary metabolites, including indole alkaloids, which have medicinal properties (Flores et al., 1987). These compounds are essential for maintaining homeostasis and have the potential to produce specialty chemicals (Devi and Sarma, 2021). Alkaloids, a type of secondary metabolite, are found in various plant families and have diverse bioactivities (Islam, 2015).

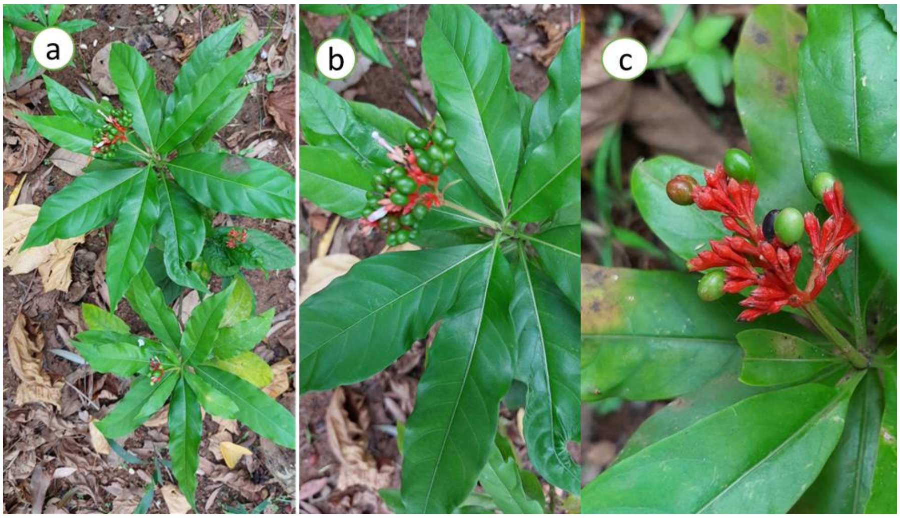

Figure 1. a) Shoot of *R. serpentina*; b) fruit set and fully grown leaves of *R. serpentina*; c) flowering set in the inflorescence of *R. serpentina*. (Photo credit: Saikat Kumar Basu)

Medicinal herbs, which are rich sources of secondary metabolites, have been used in traditional medicine for thousands of years (Sreenivasulu, 2015). Medicinal plant extracts, integral to traditional medicine, exhibit efficacy against diseases, serving as a source for drug discovery; notably, 65% of the Indian population relies on phytomedicines, and approximately 80% of the global population depends on traditional medicines, as per the World Health Organization (Boateng et al., 2016).

Importance of medicinal plants to the ecosystem and from the points of sustainability

Medicinal plants hold significant importance both ecologically and in terms of sustainability. Here are the key points:

Ecological Importance:

Biodiversity: Medicinal plants contribute to biodiversity, supporting various forms of life, from microorganisms to larger animals, by providing food and habitat.

Soil Health: Many medicinal plants help maintain soil health by preventing erosion, improving soil structure, and adding nutrients through leaf litter.

Pollination: These plants attract pollinators such as bees, butterflies, and birds, aiding in the reproduction of numerous plant species and maintaining ecological balance.

Water Cycle: They regulate the water cycle by maintaining moisture levels in the soil and contributing to groundwater recharge.

Sustainability:

Alternative Medicine: Medicinal plants offer an alternative to synthetic drugs, often with fewer side effects and lower costs, promoting health and wellness sustainably.

Economic Benefits: Sustainable harvesting and cultivation of medicinal plants can provide economic opportunities for local communities, reduce poverty, and encourage conservation efforts.

Resource Conservation: Utilizing medicinal plants can reduce the demand for conventional pharmaceuticals, often requiring significant resources and energy.

Cultural Preservation: Many indigenous and local communities have a rich knowledge of medicinal plants, and their sustainable use helps preserve cultural heritage and traditional practices.

Climate Change Mitigation: Medicinal plants can sequester carbon, helping mitigate the effects of climate change. Sustainable practices ensure that these benefits are maintained over the long term.

Medicinal plants play a crucial role in maintaining ecological balance and offer sustainable alternatives for health and economic benefits, supporting both environmental and human well-being.

Why do we need to conserve and protect medicinal plants?

Conserving and protecting medicinal plants is essential for several reasons:

- Biodiversity Preservation: Medicinal plants are a critical component of biodiversity. Protecting them helps maintain ecological balance and the health of ecosystems.
- Medical and Pharmaceutical Value: Many modern medicines are derived from plant compounds. Preserving these plants ensures a continued supply of natural resources for developing new drugs and treatments.
- Cultural and Traditional Importance: Medicinal plants hold significant value in many cultures and traditional medicine systems. Protecting them helps preserve cultural heritage and traditional knowledge.
- Economic Benefits: Medicinal plants contribute to the economy through their use in pharmaceuticals, cosmetics, and natural health products. Sustainable harvesting and conservation can provide ongoing economic benefits to communities.
- Environmental Health: Medicinal plants often play vital roles in their ecosystems, such as soil stabilization, water purification, and providing habitat for other species. Their conservation supports overall environmental health.
- Climate Change Resilience: Diverse plant species can contribute to ecosystem resilience against climate change by maintaining genetic diversity and supporting various ecological functions.

Overall, conserving and protecting medicinal plants is crucial for health, environmental stability, cultural heritage, and economic sustainability.

How can we conserve medicinal plants like *Rauvolfia*?

Conserving medicinal plants like *Rauvolfia* involves several strategies:

- Habitat Protection: Protect natural habitats where *Rauvolfia* grows. This can be done by establishing protected areas like national parks or reserves.
- Sustainable Harvesting: Implement guidelines for sustainable harvesting to ensure that plants are not overexploited. This includes limiting the amount of plant material that can be collected and ensuring that collection methods do not harm the plants.
- Cultivation: Encourage the cultivation of *Rauvolfia* in botanical gardens, farms, and community gardens. This reduces pressure on wild populations.
- Education and Awareness: Raise awareness among local communities and stakeholders about conserving *Rauvolfia* and other medicinal plants. Education programs can help promote sustainable practices and discourage illegal harvesting.
- Research and Documentation: Conduct research on *Rauvolfia* to understand its ecology, distribution, and propagation methods. Documenting traditional knowledge and uses can also aid in conservation efforts.
- Legal Protection: Enforce laws and regulations that protect medicinal plants from overharvesting and habitat destruction. This can include implementing policies at local, national, and international levels.
- Ex-situ Conservation: Establish seed banks and tissue culture facilities to conserve *Rauvolfia* genetic material outside its natural habitat. This can provide a backup in case wild populations are threatened.
- Community Involvement: Engage local communities in conservation efforts by involving them in managing and protecting *Rauvolfia* habitats. Providing incentives for conservation can also be effective.

By combining these strategies, we can help ensure the survival and sustainable use of *Rauvolfia* and other valuable medicinal plants.

Can we create a sustainable environment by conservation of important medicinal plants in India?

Yes, creating a sustainable environment by conserving important medicinal plants in India is possible and highly beneficial. Here are some key ways this can be achieved:

- Biodiversity Preservation: Conserving medicinal plants helps maintain biodiversity, which is crucial for ecosystem stability and resilience. A diverse range of species ensures natural sustainability for all life forms.
- Ecological Balance: Medicinal plants play essential roles in ecosystems, providing habitat and food for various organisms. Protecting these plants supports ecological balance and promotes healthy ecosystems.

- Cultural Heritage: Many medicinal plants have been used in traditional Indian medicine systems like Ayurveda for centuries. Conserving these plants helps preserve cultural heritage and traditional knowledge.
- Sustainable Livelihoods: Conservation initiatives can provide sustainable livelihoods for local communities. By responsibly cultivating and harvesting medicinal plants, communities can benefit economically without depleting natural resources.
- Climate Change Mitigation: Plants, including medicinal ones, act as carbon sinks, absorbing CO2 from the atmosphere. Conservation efforts can mitigate climate change by preserving and restoring plant populations.
- Scientific Research and Medicine: Protecting medicinal plants ensures they remain available for scientific research and potential new drug discoveries, benefiting global health.

➢ To effectively conserve medicinal plants, strategies could include:

- Protected Areas: Establishing reserves and protected areas where medicinal plants can thrive without the threat of habitat destruction.
- Sustainable Harvesting: Implementing guidelines and practices for the sustainable collection of medicinal plants to prevent overexploitation.
- Community Involvement: Engaging local communities in conservation efforts, providing education, and promoting sustainable agricultural practices.
- Legislation and Policy: Enforcing laws and regulations that protect medicinal plants from illegal trade and habitat destruction.
- Research and Documentation: Conducting research to document medicinal plant species, their uses, and conservation status, aiding in informed conservation strategies.

By integrating these approaches, India can create a sustainable environment that supports both ecological health and human well-being by conserving its valuable medicinal plant resources.

What is the scale of commercial needs for *Rauvol*plants in both Indian and international markets, and how do the market dynamics look?

Rauvolfia, particularly *Rauvolfia serpentina*, is a medicinal plant with significant commercial demand due to its therapeutic properties. It is commonly known as Indian Snakeroot or Sarpagandha. Here is a breakdown of its demand in Indian and international markets:

Indian Market

1. Pharmaceuticals: *Rauvolfia* is widely used in traditional Ayurvedic medicine and modern pharmaceuticals for its antihypertensive, sedative, and tranquilizing properties.
2. Herbal Medicine: There is a growing demand for natural and herbal remedies in India, boosting the market for plants like *Rauvolfia*.

3. Research and Development: Various research institutions and pharmaceutical companies are involved in studying *Rauvolfia*'s medicinal properties, driving demand.
4. Government Initiatives: The Indian government promotes the cultivation and export of medicinal plants, including *Rauvolfia*, to support traditional medicine systems and farmers.

International Market

1. Pharmaceuticals: International pharmaceutical companies use *Rauvolfia* alkaloids, particularly reserpine, to treat hypertension and mental disorders.
2. Herbal Supplements: There is a significant market for herbal supplements in the US, Europe, and other regions, where *Rauvolfia* is marketed as a natural remedy.
3. Regulatory Approvals: *Rauvolfia*-based medications are approved and used in many countries, contributing to stable demand.
4. Natural Products: Growing consumer preference for natural and organic products boosts the global demand for medicinal plants like *Rauvolfia*.

Market Dynamics

1. Cultivation and Supply: *Rauvolfia*'s supply depends on its cultivation, which requires specific climatic conditions. Any fluctuation in supply can affect the market.
2. Sustainability Concerns: Overharvesting and habitat destruction threaten *Rauvolfia* populations, prompting the need for sustainable cultivation practices.
3. Regulations and Standards: Different countries have varying regulations for medicinal plants, affecting the export and import dynamics.

Overall, Rauvolfia's commercial need is driven by its medicinal applications, which are in strong demand in both domestic and international markets. Factors like cultivation practices, regulatory frameworks, and consumer preferences for natural and herbal products influence the market.

In terms of sustainability and ecology, medicinal plants are essential. The salient points are as follows:

- Biodiversity: By offering food and habitat, medicinal plants support various life forms, from microscopic creatures to giant animals.
- Soil Health: A variety of therapeutic plants contribute to preserving soil health by reducing erosion, enhancing soil structure, and supplying nutrients through leaf litter.
- Pollination: By drawing pollinators like bees, butterflies, and birds, these plants help to reproduce a wide variety of plant species and preserve ecological equilibrium.
- Water Cycle: They help control the water cycle by preserving soil moisture levels and assisting in groundwater recharge.

- Sustainability: Alternative Medicine: Medicinal plants can sustainably promote health and wellness as a cheaper, more side-effect-free substitute for synthetic medications.
- Economic Benefits: Local populations can benefit economically from the sustainable collection and cultivation of medicinal plants, which lowers poverty and promotes environmental protection.
- Resource conservation: Therapeutic plants can decrease the need for traditional pharmaceuticals- whose pharmaceuticals- whose hose production frequently requires substantial energy and consumption- consumption- can
- Cultural Preservation: The sustainable use of medicinal herbs, which many indigenous and local groups are knowledgeable about, contributes to preserving cultural history and customs.
- Mitigation of Climate Change: By sequestering carbon, medicinal plants can lessen the consequences of climate change. Sustainable methods ensure the long-term sustainable methods ensure long-term maintenance of these benefits.

The plant's propagation is hindered by poor seed viability and low germination rates, leading to its endangerment due to prolonged overexploitation for commercially valuable bioactive constituents. Consequently, *in vitro* propagation is a means to conserve germplasms, sustainably exploit medicinal compounds, and optimize elite genotypes for genetic and phytochemical uniformity, fostering enhanced secondary metabolite production (Pathania et al., 2015). Topics such as botanical description, palynology, pharmaceutical properties, ethnobotanical practices, applications in nanobiotechnology, *in vitro* propagation, and bioinformatics are explored here. The overview of selected research works and their digests is discussed in Table 1.

Table1. Summary of selected research works on *Rauvolfia serpentina*.

Selected research works on *Rauvolfia serpentina*	References
Reserpine is one of many alkaloids in the plant.	(Monachino, 1954)
R. serpentina therapy in high blood pressure states has been reviewed up to the present time.	(Vakil, 1955)
Active chemical and pharmacological interest in *R. serpentina* have resulted in discovering several new alkaloids.	(Phillips and Chadha, 1955)
DNA bar coding provides new perspectives for forensic identification of Indian snakeroot.	(Eurlings et al., 2013)
Nodal cultures of sarpagandha could be maintained for nine months at 25°C by replacing cotton plugs with polypropylene caps as enclosures for culture tubes.	(Sharma and Chandel, 1992)
The Indian government was forced to impose restrictions on its exports to prevent complete extermination.	(Dutta et al., 1963)

Genetic fidelity of the regenerated plants analyzed by 18 ISSR markers. ISSR marker HB-12 showed a polymorphic band among the callus regenerants.	(Saravanan et al., 2011)
Vomilenine and reserpine were characterized from the analysis of the hairy roots of *R. serpentina.*	(Madhusudanan et al., 2008)
The flowers of *Agrobacterium rhizogens* mediated transformed plants were more delicate and less pigmented than the mature normal plants.	(Benjamin et al., 1993)
Major phytochemical constituents of *R. serpentina* are root indole alkaloids	(Pathania et al., 2015)
A portion of membrane proteins extracted from *Rauvolfia serpentina* facilitated the conversion of labeled strictosidine into sarpagan-type alkaloids. The enzymatic activity demonstrated a dependency on NADPH and molecular oxygen, implying that the sarpagan bridge enzyme might belong to the cytochrome P450 family.	(Ruppert et al., 2005)
Key finding proposes a novel biosynthetic pathway in *Rauvolfia*, indicating that the reduction of vomilenineen route to antiarrhythmic ajmaline may proceed through an alternative sequence of biosynthetic steps, thereby expanding the structural diversity within the monoterpenoid indole alkaloid family.	(Geissler et al., 2016)
Enzyme responsible for the formation of N-methylajmaline is found in *Rauvolfia serpentina*.	(Cázares-Flores et al., 2016)
Strictosidine synthase, an enzyme found in the Indian medicinal plant *R. serpentina*, plays a critical role in the indole alkaloid ajmaline biosynthetic pathway.	(Ma et al., 2006)
Reserpine is used as an antihypertensive and sedative agent.	(Srivastava et al., 2021)
In India, *R. serpentina* has been traditionally employed to address snakebites, manage hypertension, and treat mental illnesses. Recognized for its sedative properties, it is utilized to regulate high blood pressure and specific manifestations of mental disorders.	(Glynn, 1955)
R. serpentina has been employed since ancient times, predating the Vedic period, to address various health issues, including snake bites, insect stings, hypertension, insomnia, psychological disorders, gastrointestinal issues, epilepsy, wounds, fever, and schizophrenia.	(Vakil, 1955)
The fibrous roots are more active than the interior of the main taproot.	(Akbar, 2020)

The International Union for Conservation of Nature (IUCN) Red List classifies *Rauvolfia serpentina*, also referred to as Indian snakeroot or sarpagandha, as "Endangered" in several areas, including sections of India. Its endangered status mainly causes habitat damage, overharvesting for medicinal purposes, and a lack of sustainable production methods. Conservation initiatives are required to guarantee the continued existence of this priceless medicinal plant in India and South Asia.

Answer to the "why conservation":

It is crucial to preserve and safeguard medicinal plants for several reasons:

- Preserving Biodiversity: One essential aspect of biodiversity is the presence of medicinal plants. By keeping them safe, we can support the health of ecosystems and ecological equilibrium.
- Medical and Pharmaceutical Value: Plant-based chemicals are the source of many contemporary medications. Keeping these plants alive guarantees a steady supply of natural resources to create novel medications and therapies.
- Cultural and Traditional Importance: Many cultures and traditional medical systems prioritize medicinal herbs. By keeping them safe, traditional knowledge and cultural legacy are preserved.
- Economic Benefits: Medicinal plants used in cosmetics, pharmaceuticals and natural health products boost the economy. Sustainable conservation and harvesting practices can benefit communities economically throughout time.

Key-points to the survival strategies regarding medicinal plants:

Recreating a sustainable ecosystem in India by conserving significant medicinal plants is feasible and advantageous. Here are a few crucial methods for making this happen:

- Preservation of Biodiversity: Medicinal plant conservation contributes to biodiversity preservation, which is essential for the resilience and stability of ecosystems. A wide variety of species guarantees all life forms natural sustainability.
- Ecological Balance: Medicinal plants are vital components of ecosystems, offering food and shelter to various creatures. Preserving these plants helps maintain ecological equilibrium and fosters robust ecosystems.
- Cultural Heritage: For millennia, Ayurvedic and other traditional Indian medical systems have extensively and extensively used various medicinal herbs. The conservation of these plants aids in preserving cultural history and traditional knowledge.
- Sustainable Livelihoods: Local communities may benefit from conservation efforts by obtaining sustainable means of subsistence. By ethically growing and harvesting medicinal plants, communities can profit monetarily without diminishing natural resources.

- Mitigation of Climate Change: Plants, especially medicinal ones, take CO_2 from the atmosphere by acting as carbon sinks. Conservation activities can help mitigate the effects of climate change by preserving and restoring plant populations.
- Scientific Research and Medicine: By safeguarding medicinal plants, we can make sure they are available for future drug discoveries and scientific research, ultimately improving world health.

Among the tactics that could be used to protect medicinal plants successfully are:

1) Reserves and protected areas should be established so medicinal plants can flourish without fear of habitat loss. 2) Sustainable harvesting involves Implementing policies and procedures for the ethical gathering of medicinal plants to avoid overuse.

- Community Involvement: Educating locals, encouraging sustainable farming methods, and involving them in conservation initiatives.
- Law and Policy: Upholding rules and laws that shield medicinal plants from illicit commerce and damage to their ecosystem.
- Research and Documentation: To support well-informed conservation efforts, research is being done to document medicinal plant species, their applications, and their current state of conservation.

By integrating these strategies, India can preserve its priceless medicinal plant resources while fostering a sustainable environment that promotes ecological health and human well-being.

Answer to the "why conservation":

Indian snakeroot is a medicinal plant that requires both in-situ and ex-situ conservation techniques to be conserved and multiplied. Here are a few such tactics:

Conservation in-situ

Create and preserve protected areas where *Rauvolfia serpentina* naturally occurs, such as national parks, wildlife sanctuaries, and biosphere reserves (Surendran et al., 2021).

- Sustainable Harvesting: To avoid overexploitation, policies and procedures for sustainable harvesting should be implemented.
- Community Involvement: Ensure the local people know the value of *Rauvolfia* and reap the rewards of its preservation by involving them in conservation initiatives through educational and incentive programs.

Restoring damaged habitats where *Rauvolfia* thrives typically will increase the species' chances of surviving and proliferating.

In situ Preservation

Establish and preserve botanical gardens and seed banks to preserve ex situ *Rauvolfia* plants and seeds (Singh et al., 2007).

- Tissue Culture and Micropropagation: Use tissue culture and micropropagation procedures to grow many plants in a controlled environment.
- Farm Cultivation: Encourage *Rauvolfia*'s growth by giving farmers the tools and expertise they need to cultivate it sustainably.

Investigation and Creation

1) Genetic Research: Genetic research was needed to comprehend the diversity and adaptability of *Rauvolfia* species and generate more hardy variants.
2) Phytochemical Research: To determine and improve medicinal potential, the phytochemical characteristics must be looked at.

Law and Policy

- Regulatory Framework: Create and implement rules to safeguard *Rauvolfia* against unauthorized trading and overexploitation.
- Intellectual Property Rights: Ensure equitable benefit-sharing and intellectual property rights for traditional knowledge connected to Rauvolfia (Chakrabarti, 2014).

Consciousness and Instruction

- Public Education Campaigns: Hold educational programs to inform the general public about the value of protecting medicinal plants like *Rauvolfia*.
- Educational Initiatives: Incorporate conservation education into school and community initiatives to instill a conservation mindset in children early on.

Global Collaboration

- Collaborative Initiatives: Take part in global cooperative initiatives for the preservation and sustainable utilization of medicinal plants.
- Information Exchange: Provide global conservation networks and organizations with information and best practices.

By collectively implementing these tactics, we may contribute to the long-term preservation and propagation of *Rauvolfia serpentina* and other important medicinal plants for future generations.

The Apocynaceae family and medicinal significance of studied *Rauvolfia* spp.:

Apocynaceae Juss., situated within Gentianales (asterids, lamiids), encompasses approximately 400 genera and 5000 species distributed in tropical and subtropical regions worldwide (Endress, 2004; APG IV 2016). The family is classified into five subfamilies: Rauvolfioideae (cosmopolitan; 10 tribes/83 genera; 915 species), Apocynoideae (cosmopolitan; eight tribes/80 genera; 822 species), Periplocoideae (Old World; 33 genera), Secamonoideae (Old World; eight genera), and Asclepiadoideae (cosmopolitan; four tribes/172 genera) (Endress et al., 2014; Endress and Bruyns, 2000). Numerous taxonomic, evolutionary, and phylogenetic studies have been conducted on Apocynaceae, along with investigations into pollen morphological characteristics (Furness, 2007; Van Der Ham et al., 2001; Van Der Weide and Van Der Ham, 2012). *Rauvolfia* (Rauvolfioideae: Apocynaceae) represents a genus comprising evergreen trees and shrubs, encompassing around 85 species found across Europe, Africa, Asia, Australia, and Central and South America (Mabberley, 2017) varying in their flowering periods (Table 2). Renowned for the phytochemical 'reserpine', these *Rauvolfia* species have been extensively utilized in the treatment of hypertension (Sahu, 1983). The plants' various parts are employed in traditional medicine to address human ailments, as documented in studies by (Dutta and Virmani, 1964; Ebadi, 2007 ; Sihag and Wadhwa, 2011).

This application aligns with the broader use of herbal medicine as a secure and time-honored therapeutic approach for managing diseases and infections. Among the six Indian species within the *Rauvolfia*genus (*R. serpentina*, *R. tetraphylla*, *R. hookeri*, *R. micrantha*, *R. verticillata*, and *R. sumatrana*), only *R. serpentina* and *R. tetraphylla* are found in the Gangetic Plain of Central India and these two species are highly valued for their medicinal properties and are regularly harnessed in the pharmaceutical industry for drug formulation; unfortunately, rampant exploitation has driven them perilously close to extinction in their natural habitats. The population decline of *R. serpentina* has led to its inclusion in Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). The remaining four *Rauvolfia* species, while outside the focus of our current study, also face limitations in population size.

Table 2. Flowering seasons concerning different *Rauvolfia* species.

Species	***Rauvolfia serpentina* (L.) Benth. ex Kurz**	***Rauvolfia tetraphylla* L.**	***Rauvolfia hookeri* S.R. Sriniv. & Chitra**	***Rauvolfia micrantha* Hook.f.**	***Rauvolfiaverticillata* (Lour.) Baill.**	***Rauvolfia sumatrana* Jack**
Flowering season	October-December	October-December	Whole year	Whole year	June-September	April-December

Interestingly, except the *R. sumatrana* Jack, which is exclusively native to Andaman and Nicobar Islands, all other species are present in Tamilnadu (Sinha, 1999; 2012). *R. tetraphylla* is present in Madhya Pradesh, Uttar Pradesh, Haryana, Orissa, Punjab, and Tamil Nadu (Matthew, 1983). *R. serpentina*, also known as Indian snakeroot or devil pepper, originates from Southeast Asia's moist, deciduous forests, including India, Burma, Bangladesh, Sri Lanka, and Malaysia. Employed in traditional medicine, particularly in Kerala's Ayurveda (Blackwell, 1990), this species is experiencing a rapid decline in its natural habitat due to various ecological and biological factors. These include its limited distribution, small endemic populations, constraints in pollination, poor seed viability, and substantial anthropogenic pressure on forest land.

Consequently, *R. serpentina* is now categorized as rare and endangered (Sihag and Wadhwa, 2011). Despite the challenges, seed propagation is considered the most effective method for commercial cultivation, although it faces low and variable seed production (Bhadwar et al., 1956). *R. tetraphylla*, commonly called still tree or devil pepper (Rao, 1956), is native to Mexico, Central America, the West Indies, and northern South America. It has become naturalized in tropical regions worldwide, including Australasia, Indochina, and India; widely cultivated for ornamental purposes and traditional medicine use; various parts of the plant, such as the root, fruit, and leaves, are utilized in diverse forms like paste, powder, decoction, and juice. *R. tetraphylla* holds significance in traditional medicine, particularly for treating snakebites, with its leaves serving as an anti-venom and blood pressure remedy in Bogota, Colombia (Bussmann et al., 2018). Additionally, the peasants in San Jacinto, Northern Colombia use the leaves to alleviate tension as ethnomedicine (Bonzani, 1999).

Pollen morphology:

Rao and Shukla (1975) explored the pollen morphology of *R. serpentina*, highlighting the distinctive oblate shape as a characteristic feature of the species. Erdtman (1952) attributed the oblate amb of the single species he examined, *R. verticillata*. However, subsequent observations revealed this characteristic in other species of *Rauvolfia*. *R. serpentina* possesses a large pollen size of 47.75 ± 52 mm concerning other members of the Apocynaceae family (Tripathi et al., 2022). The formation of ectocolpi is an essential distinguishing feature for sorting species of *Rauvolfia*. The ectocolpi thickening is longer in *R. serpentina* (15.54 mm), forming a concave margin at either side of the ectocolpi (Erdtman, 1952). In R. *serpentina*, the exine exhibits a broad and thick structure, allowing for clear differentiation into a sexine and a nexine layer. The sexine's tectum presents a smooth surface without ridges and furrows. As it approaches the ectocolpi, the sexine layer appears slightly thinner, forming a wavy structure. The sexine and nexine maintain a consistent thickness, creating a seamless layer. Conversely, in *R. tetraphylla*, the tectum displays a smooth surface, and distinguishing between the sexine and nexine layers is impossible (Tripathi et al., 2022).

Agronomic practices:

For best growth, *Rauvolfia*, also called sarpagandha or Indian snakeroot, needs particular agronomic conditions. The following are essential elements for commercial *Rauvolfia* growth:

- Climate: Warm, humid climates with temperatures between 25 and 30 degrees Celsius. For rainfall, 1500-2500 mm of precipitation must fall yearly. In regions with lower rainfall, supplemental irrigation is required.
- Soil: Fertile, well-drained sandy loam or clay loam soils are ideal for *Rauvolfia* growth, optimal pH ranges from 6.0 to 7.5, which is slightly acidic to neutral. An abundance of organic

matter is desirable in soil. Growth is aided by adding compost or well-decomposed farmyard manure (Sihag and Wadhwa, 2011).

- Propagation: Fresh seeds are recommended for optimal germination. Gibberellic acid (GA_3) pretreatment increases the rate of germination. Both root and stem cuttings are necessary for propagation.
- Season: In rain-fed regions, it is best to plant at the start of the monsoon season.
- Plants should be spaced 30-45 cm apart, and rows should be 60-75 cm apart. Avoid water logging.
- Mulching: Regular weeding is required to reduce competition for moisture and nutrients. Mulching inhibits weed growth and helps the soil retain moisture.
- In the fertilization process, organic fertilizers, such as farmyard manure or compost, should be used. When necessary, balanced NPK fertilizers should be added as a supplement (Saravanan et al., 2019).

Phytochemicals and Therapeutic Virtues of *R. serpentina*:

A renowned medicinal plant in Indian and Chinese traditional medicine, it has a history of use dating back almost 3000 years, known as Sarpagandha (Swami et al., 2022). This tropical shrub, ranging from 15-60 cm in height, is a flowering plant with white and violet flowers, and its medicinal properties stem from diverse phytochemicals present in its root, stem, and leaves; the root, containing the highest concentration of these phytochemicals, is categorized into six major groups, including carbohydrates, lipids, phenolics, terpenoids, alkaloids, and other nitrogen-containing compounds (Pandey et al., 2016).

Extensive research has focused on its alkaloids' chemistry and therapeutic applications, revealing notable pharmacological effects such as blood pressure reduction and sedative actions (Nair et al., 2012). Clinical trials have successfully explored its use in neuropsychiatry, gynecological, and geriatric disorders, particularly in addressing mental health issues like anxiety, schizophrenia, bipolar disorder, epilepsy, seizures, insomnia, and sleep disorders (Singh et al., 2015). Furthermore, *R. Serpentina* demonstrates efficacy in treating diarrhea, dysentery, and gastrointestinal motility disorders and is believed to stimulate uterine contraction during childbirth. The plant exhibits variable hypoglycemic effects in diabetic patients (Arts and Hollman, 2005; Scalbert et al., 2005).

Ayurvedic pharmacodynamics:

Rasa- Tikta, Guna – Ruksha, Virya- Ushna, Vipak – Katu, Doshkarma- Kaphavatsamak (Singh et al., 2015).

Phytochemical constituents:

Rauvolfia serpentina has been a focal point of research for numerous decades, attracting researchers intrigued by its rich phytochemical composition. The plant contains a diverse array of secondary metabolites, including alkaloids, phenols, tannins, and flavonoids (Kumari et al., 2015).

Alkaloids:

Alkaloids, a diverse group of organic molecules characterized by a heterocyclic nitrogen ring, are prevalent in various organisms, with plants exhibiting a vast spectrum of alkaloid diversity. Around 10% of plant species produce alkaloids as secondary metabolites, primarily serving in defense against herbivores and pathogens (Adeyeye et al., 2019). Isolated alkaloids and their synthetic derivatives find applications as medicinal agents, offering analgesic, antispasmodic, and bactericidal effects. In *R. serpentina*, the root extract yields alkaloids that directly impact the central nervous system, reducing blood pressure compared to other antihypertensive agents.

The root is reported to contain 0.7-3.0% of total alkaloids, including approximately 0.1% of the active principle reserpine, an indole alkaloid. The structural classification of alkaloids in *Rauvolfia* encompasses weak basic indole alkaloids, alkaloids of intermediate basicity, and strong anhydronium bases (Pandey et al., 2016). Notable alkaloids identified in *Rauvolfia* include ajmaline, ajmalimine, ajmalicine, deserpidine, indobine, indobinine, reserpine, reserpiline, rescinnamine, rescinnamidine, serpentina, serpentinine, and yohimbine (Srivastava et al., 2021). Among these, reserpine stands out as a principal alkaloid with multiple clinical applications. Notable alkaloids identified in *Rauvolfia* include ajmaline, ajmalimine, ajmalicine, deserpidine, indobine, indobinine, reserpine, reserpiline, rescinnamine, rescinnamidine, serpentina, serpentinine and yohimbine (Srivastava et al., 2021). Reserpine stands out as a principal alkaloid with multiple clinical applications.

Reserpine:

This single alkaloid, known as reserpine, was initially isolated from the roots of *Rauvolfia* in 1952, and it exists in a pure crystalline form (Schlittler et al., 1954). Functioning as a relatively weak tertiary base within the oleoresin fraction of the roots, reserpine has proven efficacy in treating hypertension, cardiovascular diseases, and neurological disorders (Shamon and Perez, 2016). Notably, it is a key contributor to the antihypertensive properties of *Rauvolfia* roots. Reserpine, identified as 3, 4, 5-trimethyl benzoic acid ester of reserpic acid (Figure 2a), belongs to the indole derivative of the 18-hydroxy yohimbine type (Goel et al., 2009; Srivastava et al., 2021). As the most prominent alkaloid, reserpine serves primarily as a natural tranquilizer and has found utility in physiologic and pharmacological studies. Its antihypertensive effects stem from its depressive impact on the central and peripheral nervous systems, achieved by binding to catecholamine storage vesicles in nerve cells (Lobay, 2015).

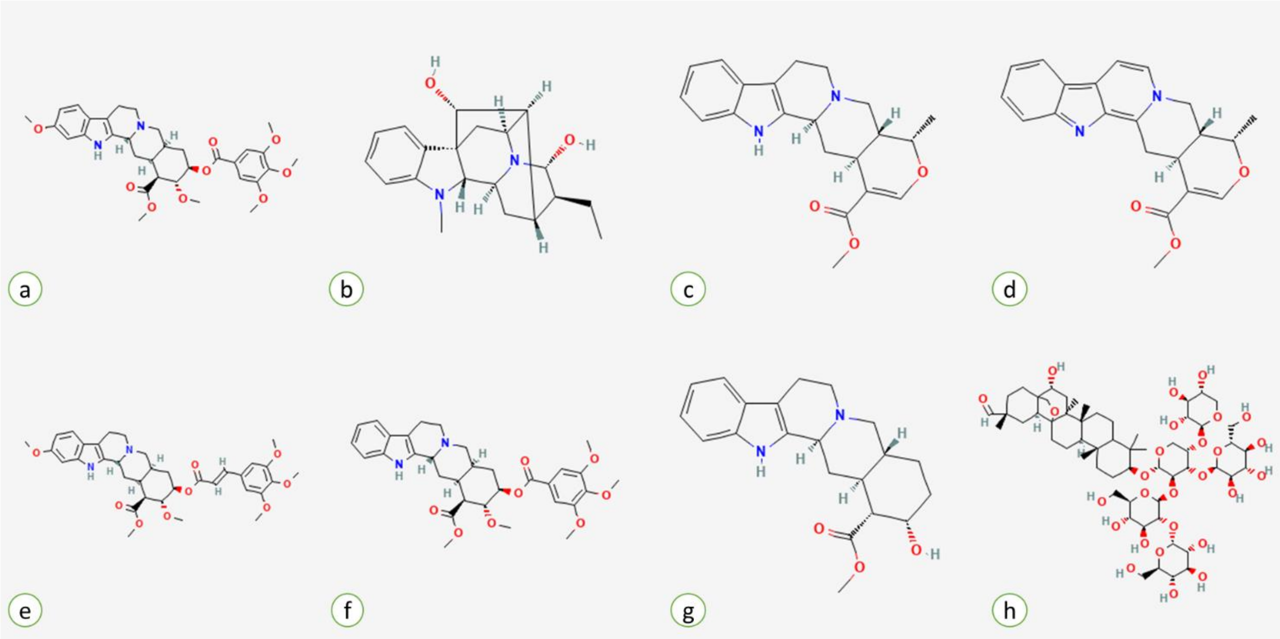

Figure 2. Representative essential phytochemicals present in *Rauvolfia*spp. (a) Reserpine (b) Ajmaline (c) Ajmalicine (d) Serpentina (e) Rescinnamine (f) Deserpidine (g) Yohimbine (h) Saponin. Source: https://pubchem.ncbi.nlm.nih.gov

This action prevents the normal storage of catecholamines and serotonin, resulting in a decline in catecholamine levels. Additionally, reserpine interferes with the autonomic nervous system by depleting transmitter substances from adrenergic neurons and potentially activating the central parasympathetic system. These mechanisms control heart rate, cardiac contraction, and peripheral resistance (Nammi et al., 2005). Furthermore, reserpine induces sedation and reduces blood pressure, particularly in cases of hypertension exacerbated by stress and sympathetic nervous system activity. The alkaloid also prompts the release of 5-hydroxytryptamine from tissues where it is typically stored, leading to increased urinary metabolites (Prusoff, 1961).

Ajmaline:

Isolated from the roots of *R. serpentina* in 1931 by Salimuzzaman Siddiqui, this compound was named Ajmaline in honor of the distinguished Unani medicine practitioner Hakim Ajmal Khan (Roy, 2018). As a class I antiarrhythmic agent derived from *R. serpentina* roots, Ajmaline proves highly valuable in diagnosing Brugada Syndrome, a rare autosomal dominant inherited cardiac disorder, and distinguishing between its subtypes (Rolf, 2003). This compound (Figure 2b), acting as a sodium channel blocker, exhibits rapid effects when administered intravenously, constituting the "Ajmaline Test" for diagnosing this type of arrhythmia (Brugada et al., 2000). Ajmaline's action on blood pressure mirrors that of serpentina. Additionally, its administration has been reported to stimulate respiration and intestinal movements. The categorization of antiarrhythmic agents includes sodium channel blockade, beta-adrenergic blockade, repolarization prolongation, and calcium channel blockade, with Ajmaline falling into the sodium channel blockade category (Liu et al., 2012).

Ajmalicine:

An alkaloid with diverse applications, plays a crucial role in treating circulatory diseases, particularly in promoting normal cerebral blood flow. Its impact on smooth muscle function not only helps prevent strokes but also contributes to lowering blood pressure. Pharmaceutical industries isolate approximately 3500 kg of ajmalicine annually from *Rauvolfia* or *Catharanthus* spp. for circulatory disease treatment (Srivastava et al., 2021). The synthetic pathway commences with geraniol, progressing through iridodial and industrial, synthesizing login. Through oxidation, loganin transforms into secologanin, enabling the formation of ajmalicine via a corynanthe-type nucleus derived from tryptamine. Ajmalicine itself originates from tryptophan, converted to tryptamine through secologanin, strictosidine, and cathenamine (Galan and O'Connor, 2006). The reduction of cathenamine to ajmalicine is facilitated by the enzymes NADPH and tryptophan decarboxylase, with the latter likely playing a key role in the synthesis of ajmalicine in *Rauvolfia,* beyond its blood pressure-lowering properties, ajmalicine restores normal cerebral blood flow by influencing smooth muscle action (Liu et al., 2012). The substantial annual isolation of ajmalicine underscores its significance in therapeutic applications (Figure 2c).

Serpentina:

Serpentina (Figure 2d), a type II topoisomerase inhibitor, demonstrates antipsychotic properties. The enzyme peroxidase plays a crucial role in oxidizing ajmalicine to serpentina, catalyzing the conversion of this bisindole alkaloid localized within the vacuole (Prusoff, 1961).

Rescinnamine:

Rescinnamine (Figure 2e), a refined ester alkaloid derived from the alseroxylon fraction in *Rauvolfia* spp., shares chemical and pharmacological similarities with reserpine, serving similar therapeutic purposes (Iqbal et al., 2013). Initially investigated in the 1950s, it found application as an antihypertensive agent for hypertension treatment. However, clinically, rescinnamine is recognized as a less potent alkaloid than reserpine, displaying lower efficacy in reducing blood pressure (Mashour et al., 1998). This compound functions by inhibiting angiotensin-converting enzyme, a peptidyl dipeptidase catalyzing the conversion of angiotensin I to angiotensin II, a vasoconstrictor substance that stimulates aldosterone secretion by the adrenal cortex (Ahmad et al., 2023). Rescinnamine's action involves the initial inhibition of ACE, followed by the blockade of angiotensin I to angiotensin II conversion. This inhibition results in decreased plasma angiotensin II levels. Given that angiotensin II is a vasoconstrictor and a negative-feedback mediator for renin activity, its reduced concentration contributes to decreased blood pressure. The subsequent stimulation of baroreceptor reflex mechanisms ultimately leads to decreased vasopressor activity and aldosterone secretion (Chen et al., 2010).

Deserpidine:

Deserpidine, an ester alkaloid derived from *Rauvolfia*, distinguishes itself from reserpine solely by the absence of a methoxy group at C-11, a modification synthesized from reserpine (Figure 2f). Its primary applications lie in its antipsychotic and antihypertensive properties (Varchi et al., 2005). Deserpidine regulates high blood pressure by modulating nerve impulses along various nerve pathways, influencing the heart and blood vessels to reduce blood pressure and alleviate psychotic behavior (Kamyab et al., 2020). Additionally, Deserpidine binds to and inhibits angiotensin-converting enzyme, competing with angiotensin I for binding at the enzyme site. This dual action inhibits the conversion of angiotensin I to angiotensin II and contributes to its antihypertensive effects (Li et al., 2014).

Yohimbine:

Yohimbine (Figure 2g) is a thoroughly characterized alkaloid with well-established pharmacological properties and is employed as a selective alpha-adrenergic antagonist or alpha-blocker in blood vessels to treat erectile dysfunction (Goldberg and Robertson, 1983). Its mechanism of action involves dilating blood vessels and enhancing blood flow to the penis, thereby improving erectile function (Andersson, 2001). Additionally, Yohimbine has been investigated as a potential remedy for diabetes, particularly in animal and human models with polymorphisms of the α2A-adrenergic receptor gene (Rosengren et al., 2010). The antagonistic effect at these receptors contributes to the relaxation of smooth muscle and a subsequent reduction in blood pressure. Yohimbine operates by elevating specific chemicals in the body, resulting in dilating the pupils of the eye (Bateman et al., 1998).

Phenols:

Recognized as secondary plant metabolites, they are widely distributed in the plant kingdom, encompassing herbs, shrubs, vegetables, and trees. Their presence serves as a deterrent to the growth of pests and pathogens within the plant, exhibiting notable antidiabetic and hypolipidemic properties, particularly in the case of *R. serpentina*, which contains a high quantity of total polyphenolic compounds (Pastrana-Bonilla et al., 2003). In medicine, phenols find utility as expectorants and emulsifying agents; moreover, the abundance of phenolic compounds signifies their potential application as antimicrobial agents, showcasing their multifaceted roles in plant defense and human health (Nair et al., 2012).

Tannins:

The antioxidative activity of tannins can be attributed to the presence of gallic acid and diagallic acid (Ellong et al., 2015). Tannins exhibit stringent properties, accelerating the healing process of wounds and managing inflammation of mucous membranes. Additionally, flavonoids, recognized as potent water-soluble antioxidants and free radical scavengers, contribute to anti-inflammatory and anticancer activities (Saravanababu et al., 2009). These properties underscore the significance of *R. serpentina* in traditional medicine practices among healers in South Eastern India, who leverage its diverse therapeutic applications in treating various disorders (Prusoff, 1961).

Flavanoids:

These powerful water-soluble antioxidants and free radical scavengers play a crucial role in preventing oxidative cell damage and exhibit robust anti cancerous activity. Additionally, flavonoids in the intestinal tract contribute to a reduced risk of heart disease. As antioxidants, flavonoids offer anti-inflammatory properties that are harnessed in herbal medicine to treat various diseases (Pastrana-Bonilla et al., 2003).

Saponins:

Saponins, glycosides of both triterpenes and sterols, have been identified in over 70 plant families (Figure 2h). Some characteristic features of saponins include the formation of foams in aqueous solutions, hemolytic activity, cholesterol-binding properties, and bitterness. Notably, saponins possess the ability to coagulate red blood cells. The elevated saponin content in *R. serpentina* underscores the use of its extracts for stopping bleeding and treating wounds, highlighting its potential therapeutic applications (Pastrana-Bonilla et al., 2003; Harisaranraj et al., 2009).

Hypertension and mental disorders:

The roots *of R. serpentina*, rich in therapeutically beneficial indole alkaloids, have been historically associated with treating hypertension. Clinical studies conducted in the mid-20th century reported successful hypertension treatment using *R. serpentina* (Dahl, 1972). Cochrane database reviews, encompassing randomized controlled trials, affirmed the effectiveness of reserpine in lowering blood pressure, recommending it as a primary antihypertensive drug (Shamon and Perez, 2016). Beyond hypertension, *R. serpentina* has demonstrated efficacy in mental disorders such as anxiety, schizophrenia, bipolar disorder, epilepsy, seizures, insomnia, and sleep disorders (Glynn, 1955). The plant's sedative properties, attributed to its oleoresin content, have shown promising results in improving the quality of life and reducing pain in migraine patients (Mittal et al., 2012; Agrawal et al., 2013).

Against snake bites:

In vivo assessment of *Naja naja* venom toxicity, including LD_{50} determination using mice (18-20 g) through range finding and median lethal dose assays, revealed a LD_{50} of 0.301 µg/g by the Miller and Tainter method. Additionally, the venom neutralizing potency (ED_{50}) was evaluated using *R. serpentina* root extract, resulting in an ED_{50} of 12.88 µg against *Naja naja* venom, with all animals exhibiting vitality and well-being throughout the acute oral toxicity study, displaying no gross toxicity, antagonistic pharmacological effects, or unusual behavior. supported by LC-MS analysis confirming the presence of bioactive compounds, findings suggest the potential of *R. serpentina* as an alternative and easily accessible antidote for snake bites, warranting further investigation (Sivaraman et al., 2020).

Miscellaneous Uses:

R. serpentina exhibits a broad spectrum of effects, including respiratory inhibition, stimulation of peristalsis, myosis, and potential utility in treating diarrhea, dysentery, and gastrointestinal motility disorders (Ezeigbo et al., 2012). Additionally, it is believed to stimulate uterine contractions, assist in childbirth, and exhibit variable hypoglycemic effects in diabetic patients. The root bark, rich in β-carboline alkaloids, has displayed anti-prostate cancer activity, making it a subject of interest for cancer research (Bemis et al., 2009).

Mineral composition and therapeutic potential:

R. serpentina is a rich source of macro and micro-nutrients, with calcium being the most abundant macro nutrient. The plant's high calcium content may contribute to its hemostatic properties, aiding in blood coagulation. Other essential elements, including zinc, suggest potential roles in managing diabetes. Ascorbic acid, riboflavin, thiamin, and niacin found in *R. serpentina* highlight its significance in herbal medicine for treating various diseases (Lobay, 2015). *R. serpentina* emerges as a valuable therapeutic herb effective in treating hypertension, psychotic disorders, and various ailments. Its ethnobotanical uses extend to circulatory disorders, intestinal issues, cholera, colic, and fever (Figure 3). The plant has demonstrated therapeutic effects in conditions like fever, malaria, eye diseases, pneumonia, asthma, AIDS, headache, skin diseases, and spleen disorders (Britto and Mahesh, 2007; Harisaranraj et al., 2009).

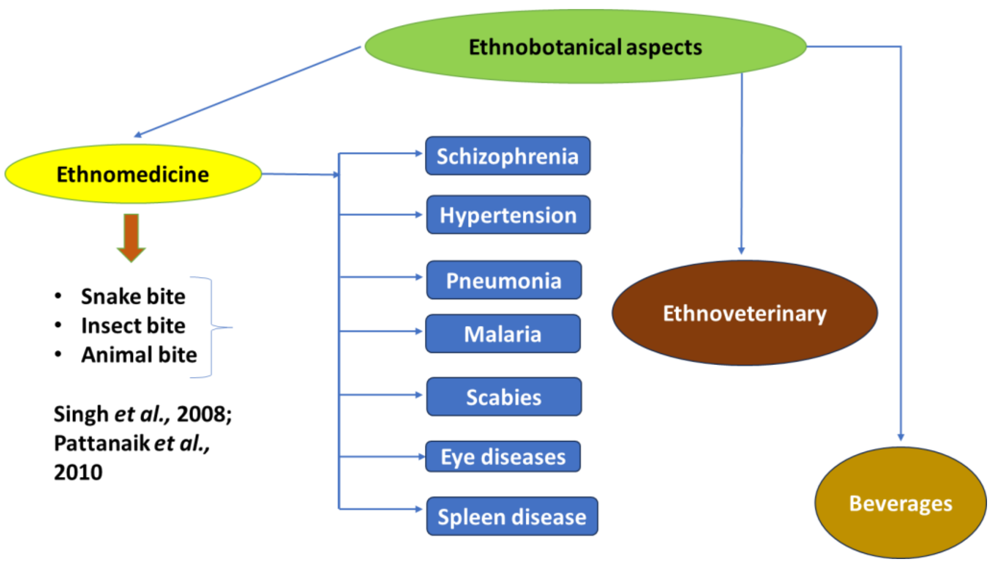

Figure 3. A schematic representation of the various ethnobotanical aspects of *Rauvolfia* spp.

Ethnoveterinary practices:

Certain villages of Madhya Pradesh involve the utilization of a combination of Sarpaganda (*R. serpentina*) roots (20-30 gm) and sugar (50-60 gm) for a period of 2-3 days, exhibiting a 60-70% efficacy in treating loose motion among tribal livestock owners; in the Nawalparasi district of Central Nepal, individuals employ a 10 g root paste or an adjusted dosage to address conditions such as fever, stomach-ache, and menstrual disorders (including heavy menstrual periods and pain during menstrual periods) until the livestock's recovery (Bhattarai et al., 1970).

In beverages:

The root bark of *R. serpentina* plays a key role in introducing bitterness to create Ranu dabai, a crucial component in the preparation of the traditional fermented beverage known as jhara, commonly utilized by rural communities in India; among tribal inhabitants in the tea gardens of Terai in West Bengal, the local use of the plant's root bark, also known as Nagbeli, imparts a bitter taste to rice beer. In cases where R. *serpentina* is abundantly available, it is a substitute for *Coccinia grandis* in the production of starter cultures (Sathe and Mandal, 2016).

In Vitro Propagation and Recent Advancements:

Chemical composition and micropropagation of *R. serpentina*:

R. serpentina is characterized by its rich content of approximately 30 indole alkaloids (0.7-2.4%), phytosterols, unsaturated alcohols, and sugars. Reserpine, renowned for its antihypertensive properties, stands out as the active constituent (Bhatt et al., 2008). Recognized for its high medicinal value and facing endangerment due to overexploitation, this species demands careful conservation efforts (Goel et al., 2009). However, challenges such as poor seed viability, low seed germination rates, and limited success in vegetative propagation through root cuttings impede the widespread commercial cultivation of *R. serpentina* using traditional methods (Bhatt et al., 2008).

In response to the growing market demand and the need for germplasm conservation, this study explores the potential of micropropagation techniques. The objective is to establish a reproducible protocol for *R. serpentina* by investigating the impact of different growth regulators, carbon sources, and light conditions on shoot multiplication. To initiate the micropropagation process, explants were meticulously sterilized using 0.1% (w/v) mercuric chloride ($HgCl_2$) for 20 minutes, followed by thorough washing with distilled water. Trimmed explants were then inoculated into Murashige and Skoog medium. Subsequent bud proliferation and shoot multiplication were facilitated by inoculating the explants in MS medium supplemented with varying concentrations of cytokinins (Table 3).

R. serpentina, in conjunction with various other *Rauvolfia* species, synthesizes a variety of terpene indole alkaloids, including but not limited to ajmaline, yohimbine, and ajmalicine. Due to the sluggish growth and challenging cultivation of *Rauvolfia*, advancements in understanding *Rauvolfia* biosynthesis have been achieved through the establishment of cell suspension and hairy root culture techniques (Stöckigt et al., 2011). The biosynthetic pathway of ajmaline in *R.*

serpentina stands out as one of the most thoroughly characterized terpene indole alkaloid pathways (Galan and O'Connor, 2006).

Table 3. Summary of micropropagation research conducted on *Rauvolfia serpentina*.

Micropropagation of *Rauvolfia serpentina*	References
The protocol demonstrated 96% bud proliferation in 14 days, achieving the highest shoot multiplication (13.3 shoots/explant, 8.2 cm average length) in MS medium+2 mg/l 6-benzylaminopurine+0.25 mg/l 1-naphthaleneacetic acid+3% sucrose, optimal rooting (73.3%) with 1/2 MS+0.5 mg/l indol-3-butyric acid, and a 90% survival rate, confirming genetic uniformity via random amplified polymorphic DNA analysis.	(Senapati et al., 2014)
Axillary bud shoot proliferation exhibited superior performance.	(Pandey et al., 2007)
The most effective rooting of adventitious shoots was observed on half-strength MS medium supplemented with 1.0 mg L-1 each of IBA and IAA.	(Salma et al., 2008)
Rooting was successfully induced in MS medium supplemented with 0.5 mol/L indole-3-butyric acid.	(Alatar, 2015)
The micropropagated, *R. serpentina* plants displayed normal growth in a nursery, with *in vitro* raised plants showing a remarkable 90-95% survival rate under glasshouse and field conditions.	(Goel et al., 2009; Kataria and Shekhawat, 2005)

Biochemical aspects and localization of enzyme:

The biosynthesis of secologanin, a precursor, initiates in the plastid and involves subsequent steps in the cytosol, with distinct enzyme activities associated with specific cellular compartments (Yamamoto et al., 2000). Strictosidine, a key intermediate, is processed in the vacuole and endoplasmic reticulum (De Carolis et al., 1990; Geerlings et al., 2000; Stevens et al., 1993). The branch point for diversification of the strictosidine aglycone occurs following strictosidinede glycosylation, leading to the formation of vindoline (Galan and O'Connor, 2006). Vindoline biosynthesis involves multiple cellular compartments such as the endoplasmic reticulum, chloroplast, and vacuole (De Carolis et al., 1990; Dethier and De Luca, 1993; Sottomayor et al., 1998; St-Pierre and De Luca, 1995).

The intricate subcellular trafficking of biosynthetic intermediates is crucial for terpene indole alkaloid biosynthesis, with some enzymes localized in specialized cells like laticifers and idioblasts (St-Pierre et al., 1999). Vascular cells are considered specialized "terpene factories" (Murata and Luca, 2005). The biosynthesis of vindoline requires at least two distinct cell types and intercellular transport mechanisms for intermediates; additionally, enzyme activity shows spatial restriction within the plant or seedling, with certain enzymes abundant in specific organs, such as roots or leaves (Vazquez-Flota et al., 1997; O'Connor and Maresh, 2006). The final distribution of alkaloids, including vindoline and bisindole alkaloids, varies across plant tissues (Verpoorte et al., 1997; Westekemper et al., 1980). A simplified pathway is presented below (Figure 4).

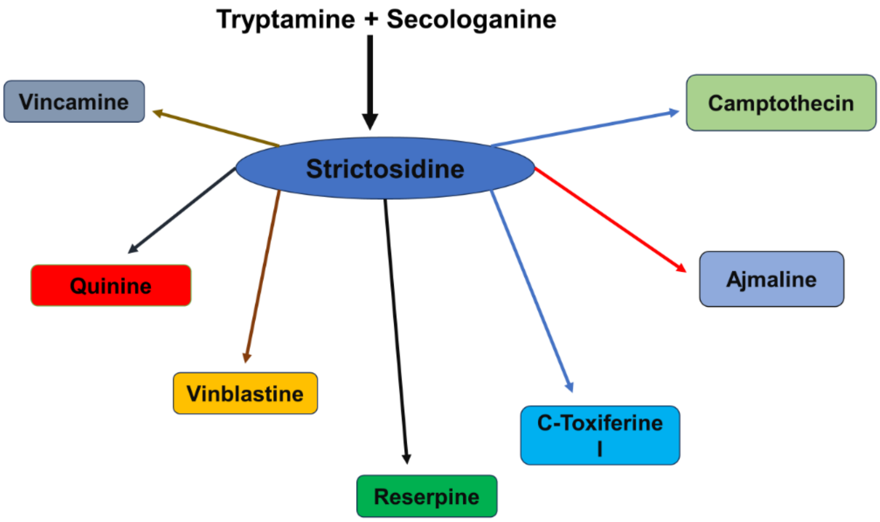

Figure 4. Schematic diagram depicts how the precursors giving rise to valuable secondary metabolites forming a biochemical pathway (a shorter approach)

Application in synthesizing nanoparticles:

Silver Nanoparticles (AgNPs) were synthesized using an eco-friendly and cost-effective method involving the leaf extract of *R. serpentina*. The plant extract served as a reducing and stabilizing agent for the AgNPs. It demonstrated antimicrobial activity against human pathogenic microorganisms, larvicidal activity, and cytotoxicity against HeLa and MCF-7 cell lines suggest that the AgNPs derived from *R. serpentina* have potential applications in various biological activities, making them promising candidates for further research and development (Panja et al., 2016).

SerpentinaDB:

SerpentinaDB is a structured compilation of 147 Plant-Derived molecules (PDMs) from *R. serpentina* (Figure 5b), a medicinally important plant endemic to the Himalayan Mountain ranges of the Indian subcontinent (Pathania et al., 2013, 2015; Varnika et al., 2020). The database provides comprehensive information on the physicochemical properties, plant part source, chemical classification, IUPAC, SMILES, and 3D chemical structures of these molecules, along with associated references (Ye et al., 2011). SerpentinaDB offers a user-friendly web interface for data query and *extraction*, allowing users to search for molecules based on plant part (Figure 5a), chemical class (Figure 5b), or specific physicochemical properties; additionally, the database provides a similarity search option against the ZINC database (http://zinc.docking.org/) to identify analogues of natural molecules at user-defined cut-off values.

The purpose of Serpentina DB is to facilitate the use of natural chemical diversity for drug discovery by providing a comprehensive resource of *R. serpentina* molecules for rational prospection of therapeutic molecules (Pathania et al., 2015). The database has been demonstrated to be helpful in identifying novel aldose reductase inhibitors for the intervention of complications of diabetes (Pathania et al., 2015). Established repositories of natural compounds, including Naturally Occurring Plant-based Anti-cancer Compound-Activity (NPACT) (Mangal et al., 2013), Super Natural (Dunkel, 2006) and Herb Ingredients' Targets (Ye et al., 2011) address various functional dimensions within PDM libraries. While certain databases concentrate on specific diseases or target-compound interactions, others encompass plants from distinct geographical regions (Ntie-Kang et al., 2013). The highly basic anhydronium base serpentina demonstrates both anticancer and anti-malarial properties. Its mode of action, akin to other anhydronium bases, is explained through DNA-intercalation and inhibition of topoisomerase II (Dassonneville et al., 1999).

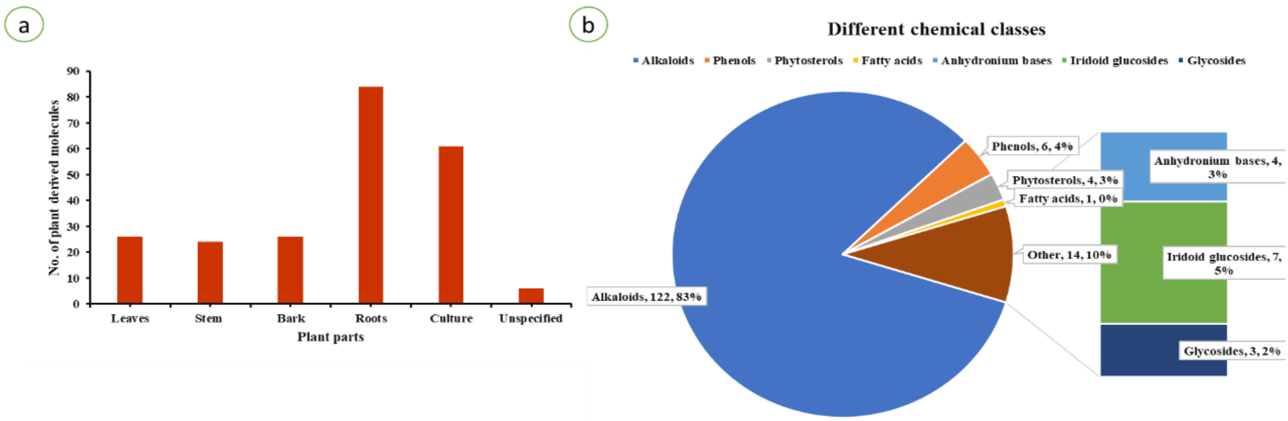

Figure 5. Distribution of different chemical classes and their quantitative presence across various *R. serpentina* plant parts

The value of therapeutic plants from an ecological and sustainability standpoint:

By a variety of means, medicinal plants are essential for preserving ecological balance. They improve biodiversity by offering food and habitat to a diverse spectrum of life forms, ranging from microbes to larger animals. These plants also improve soil health by reducing erosion, enhancing soil structure, and replenishing the soil with nutrients through their leaf litter. Medicinal plants help many plant species reproduce by drawing pollinators such as bees, butterflies, and birds, promoting ecological stability (Ghazoul, 2005). Additionally, by preserving soil moisture levels and promoting groundwater recharge—both critical for the maintenance of ecosystems and agricultural productivity—medicinal plants play a critical role in controlling the water cycle.

When considering alternatives to synthetic pharmaceuticals, medicinal plants provide less expensive and less adverse effects, making them a more sustainable option. Sustainable plant production and harvesting can lower poverty, increase economic opportunities for nearby communities, and support conservation initiatives (Thrupp, 2000). Medicinal plants can lessen the adverse effects that the manufacture and use of conventional drugs have on the environment, which helps conserve resources.

Additionally, the sustainable use of medicinal herbs contributes to the preservation of traditional knowledge and cultural legacy, especially among indigenous and local groups who have an important understanding of these plants. Furthermore, when maintained responsibly, medicinal plants can sequester carbon, aiding in the fight against climate change (Kumar, 2006).

Because of its medicinal qualities, *Rauvolfia* - especially *Rauvolfia serpentina* - is a plant that is in high demand commercially. It is frequently referred to as sarpagandha or Indian snakeroot. The demand for it in Indian and global markets is broken down as follows:

- Indian Market Pharmaceuticals: Due to its sedative, tranquilizing, and antihypertensive qualities, *Rauvolfia* is a common ingredient in both contemporary and traditional Ayurvedic medicine.
- Herbal Medicine: The increasing demand for natural and herbal treatments in India is stimulating the market for plants like Rauvolfia.
- Research and Development: The medical benefits of *Rauvolfia* are being investigated by several academic institutions and pharmaceutical firms, which is fuelling demand.
- Government Initiatives: To support farmers and traditional medical systems, the Indian government encourages the growth and export of medicinal plants, including *Rauvolfia*.
- Pharmaceuticals for the International Market: Reserpine, one of the *Rauvolfia* alkaloids, is used by pharmaceutical companies in other countries to treat mental illnesses and hypertension.
- Herbal Supplements: *Rauvolfia* is sold as a natural cure in the US, Europe, and other places, with a sizable market for herbal supplements (Kumar et al., 2020).
- Regulatory Approvals: Drugs based on *Rauvolfia* are authorized and in use in numerous nations, which helps to maintain a steady demand.
- Natural Products: The market for medicinal plants like *Rauvolfia* is increasing globally due to consumers' growing preference for natural and organic products.
- Cultivation and availability: *Rauvolfia* cultivation, which necessitates particular climatic conditions, determines its availability. Any changes in the supply may impact the market.

- Sustainability Concerns: *Rauvolfia* populations are at risk due to overharvesting and habitat damage, highlighting the need for sustainable production techniques (Sharma and Pandey, 2012).

Conclusions:

R. serpentina emerges as a botanical treasure with profound medicinal significance, encompassing a rich repertoire of phytochemicals and therapeutic virtues. As a member of the Apocynaceae family, *Rauvolfia* species, particularly *R. serpentina* and *R. tetraphylla*, have been integral to traditional medicine practices across the Indian subcontinent. The phytochemical constituents, notably alkaloids such as reserpine, ajmaline, ajmalicine, serpentina, rescinnamine, deserpidine, and yohimbine, underscore its diverse pharmacological applications, ranging from antihypertensive and antiarrhythmic effects to potential remedies for mental disorders, snakebites, and various ailments. The challenges faced by *Rauvolfia* species, including poor seed viability, low germination rates, and overexploitation, necessitate innovative approaches such as *in vitro* propagation for conservation and sustainable exploitation. Beyond its therapeutic applications, *R. serpentina* demonstrates versatile uses, ranging from ethnoveterinary practices to the production of traditional fermented beverages. The plant's mineral composition further adds to its therapeutic potential, with macro and micro-nutrients contributing to its hemostatic properties, antidiabetic potential, and roles in managing various disorders.

The exploration of pollen morphology provides insights into the distinctive features of *R. serpentina*, contributing to its taxonomic characterization. Additionally, advancements in understanding the biosynthetic pathways of key alkaloids, such as ajmaline, offer avenues for targeted research and cultivation practices. In the context of contemporary scientific advancements, the role of synthesizing nanoparticles highlights its potential applications in nanobiotechnology. The eco-friendly synthesis of silver nanoparticles using *R. serpentina* leaf extract showcases its multifaceted contributions to modern research and development. *Rauvolfia serpentina* is a bioactive treasure that requires careful protection and investigation into its possibilities in nanotechnology and medicine. It bridges the gap between traditional wisdom and contemporary science. Its pharmacological components, essential for managing diseases like hypertension, emphasize its health advantages. *Rauvolfia serpentina* is vital to preserving biodiversity, which is in jeopardy due to deforestation and climate change. Preserving it helps support other species that depend on its environment and protects biodiversity and cultural heritage. Beyond conventional medicine, their molecules in pharmacology pique interest since they present a variety of therapeutic possibilities for drug creation. Thus, protecting *Rauvolfia serpentina* symbolizes accountability, fusing conventional knowledge with cutting-edge research for a sustainable future where human health and biodiversity coexist.

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Chapter- 3

Renewable Energy and the Future of India

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Keywords: Renewable Energy, Non-renewable Energy, Environment, Future of India, Pollution control

Abstract:

The progress of a nation depends upon its power to supply energy to the country and its ability to meet the crises of other countries. The development of a country also depends upon its capability to protect the planet from environmental pollution and degradation caused by the activities carried out in the country itself. This paper aims to find how far India has progressed and what the prospects are for India with respect to the use of renewable energy resources. The paper also attempts to find how India has been taking measures to control and resist environmental pollution by shifting towards environmental pollution. The paper highlights the merits and demerits of renewable energy sources and the challenges to be met for proper utilization of renewable energy sources and advancement in the country's future developmental projects. The goals adopted to enhance the future development of India with the help of renewable energy sources have been brought to light. The move towards a green revolution, marked by keeping the utility of renewable energy in tune with the preservation of human health and the nation's natural green strategy, has been focused on in this paper.

Introduction:

The word "energy" derives from the Greek "energeia" and is believed to appear first in the work of Aristotle in the fourth century BC. However, over time, energy came to refer to the capacity or power to do work. In conformity with the law of energy conservation, which states that energy can be converted or transformed but not created or destroyed, energy gets transformed into many forms. It exists in different forms like potential, kinetic, thermal, chemical, electrical, nuclear, bio-mass energy and others. The sun is the prime energy source since the core particle of energy is born and created in the heart of the sun, and it also radiates solar energy that makes life possible on Earth.

Energy is one of the most essential components for the functioning of the living and nonliving domains of the universe. Broadly differentiated into two categories called renewable and non-renewable energies, the management of different types of energy supply is contrived to meet the demands of the growing population. In a country like India, alternative energy is

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highly required to meet the needs of the massive growing population. The dreadful fear of exhaustion of conventional energy sources in the future and the *hazardous influences of burning fossil fuels* that are leading to massive environmental pollution and impacting the global ecosystem by the emission of greenhouse gases and also increasing carcinogenic elements in the environment have led technologists and scientists to focus on the mass generation of renewable energy sources globally (Azarpour et al., 2012).

Modernization and advancement in society and civilization are not possible without a sufficient energy supply, and for this reason, the use of alternative, renewable and sustainable energy is the need of the hour. However, it is essential to find out first whether a country like India can afford to maintain quality sustainable means for the production and storage of renewable energy to cater to the demands of the vast population uninterruptedly. It is also important to find out whether Renewable energy can solve all the problems related to power generation. Abbas Azarpour comments *that a common misconception of renewable energy (RE) is that it could serve as a holistic solution to the problems associated with the disreputable yet reliable fossil fuel and nuclear energy* (Azarpour et al., 2012).

Increased demand for renewable energy may lead to the Green Energy revolution:

In keeping with India's goal of securing 500GW renewable energy capacity by 2023 (Wikipedia Contributors, 2019), the installed renewable energy capacity is being monitored to experience a positive upsurge curve. Various plans and projects are being initiated to improve the upsurge of renewable energy. In the near future, India will most likely witness an upsurge in using renewable energy to produce green hydrogen. For the most part, green hydrogen is generated by renewable energy. The greener hydrogen is produced, the more renewable energy will be required, automatically increasing renewable energy supply and conservation to meet the high demand for renewable energy. Green energy produced from renewable energy produces green ammonia, a main ingredient of synthetic fertilizer and is also used for long-duration grid energy storage and seasonal energy storage (Khan et al., 2018).

The Ministry of New and Renewable Energy (Hydrogen Division) under the Government of India has taken the initiative to maximize the production of Green Hydrogen and its derivatives in India under the National Green Hydrogen Mission on 28th June 2023 (*Ministry of New & Renewable Energy - Government of India*, n.d.). In this regard, the Solar Energy Corporation of India (SECI) has been directed to implement an agency for the implementation of this scheme and cater to the demand for power supply in the form of solar energy and wind energy as the most effective renewable energy sources for the purpose. Most importantly, the mission has gained the approval of the Honourable Minister of Power and New and Renewable Energy in India. Since numerous governments have adopted policies to promote the commercialization of green hydrogen, its production is expected to increase significantly in the future. Along with this, the demand and increase in the production of renewable energy supply and sources will undoubtedly witness tremendous upsurge in the coming days in India. About the future of green energy, Sanjukta Banerjee (2019) has declared *that these have no adverse effect on the planet and won't replenish.*

Another attempt to focus attention on Renewable energy is celebrating World Wind Day annually on June 15th (Figure 1). The words *"The development of wind energy will play an important role not only in solving the problem of electricity supply but also in solving the economies of nations and environmental sustainability around the world*" ring a note of optimism (Abdurahmonov et al., 2022).

However, there are constraints to make it a smooth path of progress. Most renewable energy sources, such as solar and wind, are intermittent in nature. They depend on weather conditions, meaning they may only sometimes be available when demand is high or at certain times of the day. This intermittency challenges grid stability and requires energy storage solutions to balance supply and demand effectively. The availability and suitability of specific renewable resources vary depending on the location. For example, solar power may be more viable in sunny regions, while wind power may be more feasible in areas with consistent wind patterns. Developing efficient and cost-effective energy storage technologies is crucial to address the intermittency of renewable energy sources. Storage technologies like batteries and pumped hydro are being used, but advancements are still needed to store large amounts of energy for extended periods (Inhaber, 1979; LeninBabu and GowriManohar, 2023).

Figure 1. Wind energy has evolved successfully as an essential source of renewable (alternate) energy across the planet (Photo credit: Saikat Kumar Basu).

Still, it can be noted that the renewable energy sector will become a significant driver of job creation and economic growth in India in the future. Investments in non-conventional energy projects will lead to new employment opportunities in the manufacturing, installation, operation, and maintenance of renewable energy infrastructure in India in the future. Nath and Sen support this view and assert that *it greatly influences economic growth, job creation and energy security* (Nath and Sen, 2021). It will stimulate local economies and foster innovation in the clean energy sector in the coming days.

Renewable energy can revolutionize the telecom sector:

Renewable energy is revolutionizing the mobile sector. On the other hand, the mobile sectors are investing in renewable energy infrastructure (solar panels and wind turbines) (Figure 2) to reduce their reliance on conventional energy sources. Telecom industries in India have begun to utilize renewable energy sources like solar power. They are taking initiatives to build solar tower sites to minimize carbon usage in the industrial sectors in the coming days. By initializing renewable energy like solar power and wind power, the mobile sectors will mitigate environmental pollution and fight climate change caused by burning fossil fuels. So far, the prolonged consumption of conventional energy resources like fossil fuels and their extractions has proved to be more challenging and costly; because of that, a shift towards renewable energy has become more popular. Bansal has carefully pointed out *this factor; the increasing depletion rate of conventional energy sources has emphasized renewable energy sources such as wind, micro-hydro, biogas, etc.* (Bansal et al., 2003) (Figure 3).

Figure 2. Mobile sectors invest heavily in wind turbines for a steady supply of green energy like wind energy (Photo credit: Saikat Kumar Basu).

Using renewable energy in the mobile and telecom sectors is expected to eliminate the need for costly grid infrastructure and reduce transmission losses to the minimum level shortly. H. Inhaber has aptly highlighted the problems and difficulties of using unconventional energies. *The risk from nonconventional energy sources derives from the large amount of material and labor needed, along with their backup and storage requirements* (Inhaber, 1979). Using renewable energy in the telecom industry will lead to long-term energy savings and will also act as a safeguard against future energy price fluctuations.

Figure 3. A model micro-hydro project from Lethbridge, Alberta, Canada (Photo credit: Saikat Kumar Basu).

Many renewable energy sources have reached or are appropriating cost parity with conventional energy sources, making them economically viable options for power generation. Adopting non-conventional energy resources aligns with several Sustainable Development Goals (SDGs) set by the United Nations, including affordable and clean energy, climate action, and promoting sustainable industrialization and innovation. V. Siva Reddy has rightly observed *that using renewable energy sources is one of the crucial components of sustainable development* (Reddy et al., 2013).

Conventional energy sources, especially coal and oil, are significant sources of air pollution. Burning these fuels releases harmful pollutants, including particulate matter, sulfur dioxide, nitrogen oxides, and volatile organic compounds, contributing to respiratory illnesses and other health problems. Shifting to cleaner, non-conventional energy sources will improve air quality and public health. Fossil fuels are finite resources and their reserves are depleting over time. Depletion of conventional resources is also pinpointed in the quoted words, *widespread shortages of the traditional fuels on which an estimated one-half of the world's population relies for cooking and other energy needs* (Hughart, 1979). The finite nature of fossil fuels necessitates a more effective transition towards sustainable and renewable energy sources to ensure a stable and secure energy supply in the future of India.

Though the costs of renewable energy technologies have decreased, they can still be higher than traditional fossil fuel-based energy sources. The initial investment and installation costs may pose challenges for developing countries or regions with limited financial resources. Some non-conventional energy sources, like solar and wind, have lower energy densities than fossil fuels. This means larger installations will be needed to generate the same amount of energy, impacting land use and requiring more substantial infrastructure investments. For procuring sufficient renewable energy, A. Aravani emphasizes the need for proper *Supply infrastructure, technology readiness, human resources capabilities and geographic elements* (Iravani et al., 2017).

More advancement in renewable energy technologies is essential to increase efficiency and reduce costs. However, research and development in this area may need more funding constraints and technological barriers. The public's perception and acceptance of non-conventional energy sources can influence their implementation. Some people may be concerned about certain renewable energy installations' aesthetics, noise, or perceived health effects.

The availability and suitability of specific renewable resources vary depending on the location. For example, solar power may be more viable in sunny regions, while wind power may be more feasible in areas with consistent wind patterns. Inconsistent or inadequate policies and regulations can hinder the growth of renewable energy in the future. Supportive policies, incentives, and long-term planning are crucial to encouraging investments in clean energy (Gielen et al., 2019). Despite various challenges, efforts to address them are ongoing, and technological advancements and supportive policies are gradually overcoming these obstacles. As renewable energy is becoming more integrated into the energy landscape, the benefits of clean, sustainable power generation are likely to outweigh the challenges and bring many benefits in the future, and the contribution of the telecom sector in fighting the challenges is undeniable. K A. Khan observed *that the renewable energy sector has one huge advantage over fossil fuels because it is highly ecologically acceptable compared to fossil fuels* (Khan et al., 2018).

Building economic prosperity by enhancing the efficiency of renewable energy sources and own supply chains:

As per the International Energy Agency (IEA) declaration, a global renewable energy capacity growth of 107 gigawatts (GW) is estimated in 2023. The IEA has also estimated an expected increase of electric vehicles by 35 % this year. For this reason, photovoltaic solar panels, wind turbines and lithium-ion batteries for renewable energy storage require an enormous manufacturing boost. Besides, a massive increase in the production of rare Earth minerals has become highly necessary. Hence, the demand for production and increasing manufacturing capacity of solar panels, wind turbines and lithium-ion batteries, supposed to be the catalysts for a green energy revolution, are fuelling a gold rush in the present scenario.

The untapped rare Earth minerals have become the best choice for countries around the world to build their supply chains and try to reserve lithium and cobalt as much as possible. China has been able to establish a monopoly market power in this regard. However, developing countries rich in rare Earth minerals are trying to grab maximum profit by harnessing a complete process of domestic energy supply rather than exporting the primary raw materials to China, the US, and other countries. As per the report by ABC News, India is set to establish regional renewable energy value chains rather than meeting the demands of the international interest. The report by Anupam Nath and SIBI Arasu in Associated Press and ABC News on July 19th, 2023, says that India wants to expand its critical mineral mining operations. The report also says that plans are set for India to propagate and maintain its clean energy infrastructure in a complete cycle from beginning to end. Recent times have witnessed the increased efficiency of solar panels with the application of a layer of chromium on them. This mineral is also used in wind turbines and batteries as renewable energy sources. Increased efficiency of the renewal energy sources (Figure 4) is undeniably resulting in higher energy output yield to meet India's growing population's demands.

Figure 4. Micro-hydro projects are growing fast as an affordable and sustainable alternative renewable energy resource (Photo credit: Saikat Kumar Basu).

For sixty years, the dusty mountain, rich in minerals at Kaliapani, a village in the Jajpur district of Odisha, has been a mining site for chromium, used as a coating on solar panels and wind turbines for higher yield of renewable energy. Other minerals like Lithium, Cobalt and Nickel, used in solar panels, wind turbines and batteries for increasing the output of renewable energy, are also being discovered in India at an accelerating rate for building improved green infrastructure in India to meet the escalating demand in the country and bolster mineral supply chain for the production of renewable energy worldwide. Umair Shahzad said, "*The most significant feature of renewable energy is its plentiful supply." It is infinite* (Shahzad, 2012). Increased efficiency of the sources of renewable energy supply due to the use of mineral coatings produced in the country itself will continue to enhance the supply of renewable energy in India and aid in developing its socio-economic conditions in the future. In the words of Naruttam K. Roy, *Power is the most significant criterion of development, and the level of development of a society is measured by the amount of power consumed* (Prospects of Renewable Energy Source, nd). In the same vein, Mohamed M. Khalil (2022) has also observed *that renewable energy resources can be recreated and renewed, and the world cannot run out of them.*

Conclusion:

As the world faces environmental challenges and seeks long-term sustainability, a growing emphasis on transitioning towards renewable energy sources to mitigate climate change and ensure a more sustainable future is inevitable. India's mission to increase the production of Green Hydrogen will likely escalate the demand for renewable energy. Utilization of renewable energy in the telecom industry can succeed in reducing reliance on conventional energy and thereby fight environmental degradation and climate change in the long run. By embracing non-conventional energy resources and accelerating their deployment, India can address the challenges posed by climate change, promote environmental sustainability, improve energy security, and pave the way towards a more prosperous and resilient future for all Indians.

Though it is essential to have advancements and a better future for renewable energy, it must be remembered that the cost factors for availing the opportunities for harnessing such renewable energy are huge and prove challenging for countries like India, where people are still struggling with sustainable living concerns. However, one cannot shrug that the environmental issues and the health hazard conditions become alarming due to the negative influences of such advancements where by-products and residues emerged from such developmental projects as mining, causing greater damage to the local and neighboring villagers and the environment. Chronic exposure to chromium leads to health problems, toxicity, land impoverishment, damage to agriculture, and potential environmental degradation.

The mission of building up whole supply chains domestically to reap maximum utility in the generation of renewable energy and bringing about the green energy revolution should, thus, most essentially focus on the fact that India must take care and resist the harmful impacts on environmental degradation so that the Indians will not have to depend on anyone for fulfilling our economic and climate goals in the future.

Last, the wide range of renewable energy uses, from the minor household activities of day-to-day life to its innovative use in space research exploration, is a step forward in India's developmental goals. The use of solar panels on all four sides of Chandrayaan 3 Lander to ensure that it continues to draw solar power and remains active, even if it lands in a wrong direction or tumbles over, is a milestone concerning the present status of India's use of renewable energy source. Such more advanced technological uses of renewable energy sources in space studies will likely lead India to a bright future by winning over its significant challenges.

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Chapter- 4

Reproductive Ecology of Plants: A Key Approach to Effective Conservation

Alokemoy Basu

Keywords: Biodiversity Conservation, Conservation Biology, Plant Reproductive Ecology, Pollination Dynamics, Seed Dispersal

Abstract:

Pollination ecology, or reproductive ecology, represents one of the most fascinating and holistic interactions between plants and animals. Various animals, at least during a part of their lifecycle or livelihood, depend on plants for food, shelter, mating grounds, or breeding sites. In return, plants share their valuable resources with these animals, intentionally or unintentionally, as part of a reciprocal relationship. Plants entrust animals with the task of transferring pollen grains to suitable stigmas and seeds to appropriate germination beds (soil). To ensure the success of this interaction, plants have adapted and co-evolved to meet the animals' needs, making themselves inseparable from the ecological niche of these animals. This relationship builds an ecological equilibrium so strong that the entire ecosystem could collapse if a single element is removed. Therefore, studying and understanding the relationships between all organisms within the biosphere is crucial. Knowledge will guide the development of sustainable conservation strategies that, to some extent, can heal the environment and protect it from further harm.

Introduction:

Reproduction is one of the most significant characteristics that differentiate living entities from non-living ones. The perpetuation of life on Earth necessitates the creation of replicas of individuals, allowing the transmission of genetic material to the next generation. Therefore, reproduction can be defined as the multiplication of individuals within a species at a given time, ensuring the sustenance of that species. Angiosperms reproduce both sexually and vegetatively. In vegetative propagation, a clone of an individual is produced without any genetic variation. Genetic variation among individuals of a species is essential to maintain adaptability in response to a changing environment, ensuring the population's survival over time. This genetic variation is achieved only through sexual reproduction, as half of the genetic material of any plant is contributed by the female parent and the other half by the male counterpart. Regarding non-nuclear genes (mitochondrial and chloroplast genes), the contribution of females is slightly higher.

Angiosperms release two types of disseminules into nature during sexual reproduction: pollen grains, released before fertilization, and seeds, released after fertilization. The reproductive success of any plant depends on whether the disseminules released without control can reach their respective destinations. A pollen grain must reach the receptive surface of a

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compatible stigma, where it can germinate. Given the uncertainty in pollen transport, only a tiny fraction of the pollen grains produced by a flower successfully reach a compatible stigma. Additionally, each species has a fixed pollen longevity. A pollen grain that fails to reach a receptive stigma within its viability period is useless to the plant. Therefore, the primary requirement for successful sexual reproduction is the transfer of viable pollen grains from the anther to a receptive stigma, a process known as pollination. Successful pollination often requires the active involvement of biotic or abiotic agents, a process facilitated by the flower's intricate morphological and physiological characteristics (Mandal, 2020). In cases where animals are involved in pollination, flowers offer various attractants and rewards. These flowers are designed in such a way that their functional organs, the androecium and gynoecium, remain well protected.

Seeds carry the embryo of the future plant. Like pollen grains, the successful placement of a seed in a suitable environment is essential for germination and, ultimately, the development of a new individual. To disperse seeds over long distances, plants adopt several morphological modifications in seeds and seed-bearing organs and utilise biotic and abiotic agents.

Due to the increasing human population and resulting habitat destruction, along with other anthropogenic effects, the rate of plant species extinction is rising. According to the IUCN (1998), there are currently over 270,000 extant plant species; of these, approximately 34,000—or one in every eight—are endangered. Many have become regionally threatened, and it is estimated that nearly 25% of plant species are at risk of extinction within a few generations (Raven, 1987). Both in situ and ex-situ conservation of plant species is crucial to mitigate this loss. In situ conservation ensures the preservation of habitats, thus protecting both plants and their associated organisms, such as biotic vectors (Pence, 1999). In this chapter, the pollination ecology from the perspective of both plants and their pollinators will be discussed to formulate a possible holistic approach to biodiversity conservation.

Biotic Pollinators

According to Baker et al. (1971), pollinators can be classified into major and minor. Minor pollinators visit various types of flowers within their locality, feeding on nectar and pollen grains and occasionally conducting accidental pollination. They are not dependent on a specific plant or group of plants, nor are the plants dependent on them. For example, even a boy climbing a Jujube (Kul) tree may unintentionally pollinate some flowers simply by shaking the flowering branches together. Who would have thought that *Homo sapiens sapiens* could be a pollinator of *Ziziphus jujuba*? However, *Ziziphus jujuba* produces fleshy pulp and nectar as rewards, not only to attract its primary pollinators but also to engage other animals, including humans, in pollination without them realizing it.

On the other hand, significant pollinators are more focused and effective than minor ones. These pollinators, mainly insects, depend on the flowers for food, shelter, breeding places, or a combination. The relationship between plants and insects is dynamic in evolutionary terms. It is rare to find a one-blossom-one-pollinator relationship. The relationship should be viewed from both the plant's and the pollinator's perspectives, schematically represented below, for better understanding (Faegri and Van Der Pijl, 1979).

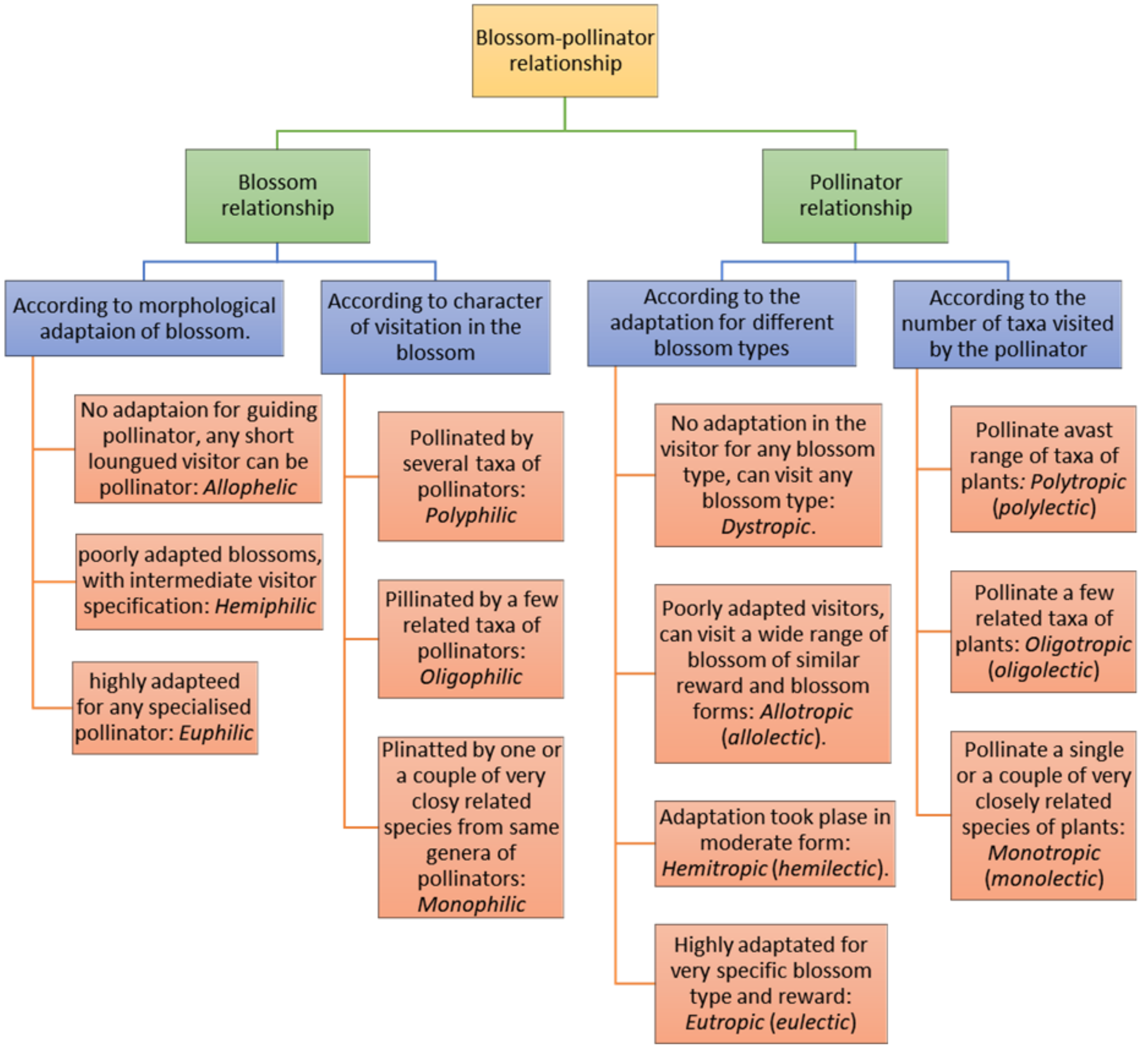

Figure 1. The schematic representation of blossom *vis-à-vis* pollinator relationship.

A monotropic visitor (Figure 1) typically does not visit any other plant species except for its preferred ones. Cruden (1972) suggested that oligolectic bees switch their pollen sources only without their preferred pollen. Suppose a specific population of bees thrives on and adapts to alternative pollen sources. In that case, there must be a genetic factor at play, potentially leading to the development of a new strain. However, in addition to absolute monotropy, there may be instances of geographically induced monotropy, where only one species of the desired pollen flora of an oligolectic visitor is present (e.g., the monotropic relationship between Cucurbitaceae and specialized bees, as described by Hurd et al. in 1971).

On the other hand, from the perspective of the blossom, monophily represents a more advanced trait. Polyphilic or oligophilic species are less specialized in floral architecture, allowing a more comprehensive range of visitors to access the flower, as all of them may serve as potential pollinators. However, these blossoms have less protection against nectar and pollen theft, which can result in no pollination. This is considered a primitive characteristic, typically adopted by a species when it is establishing itself in a new environment.

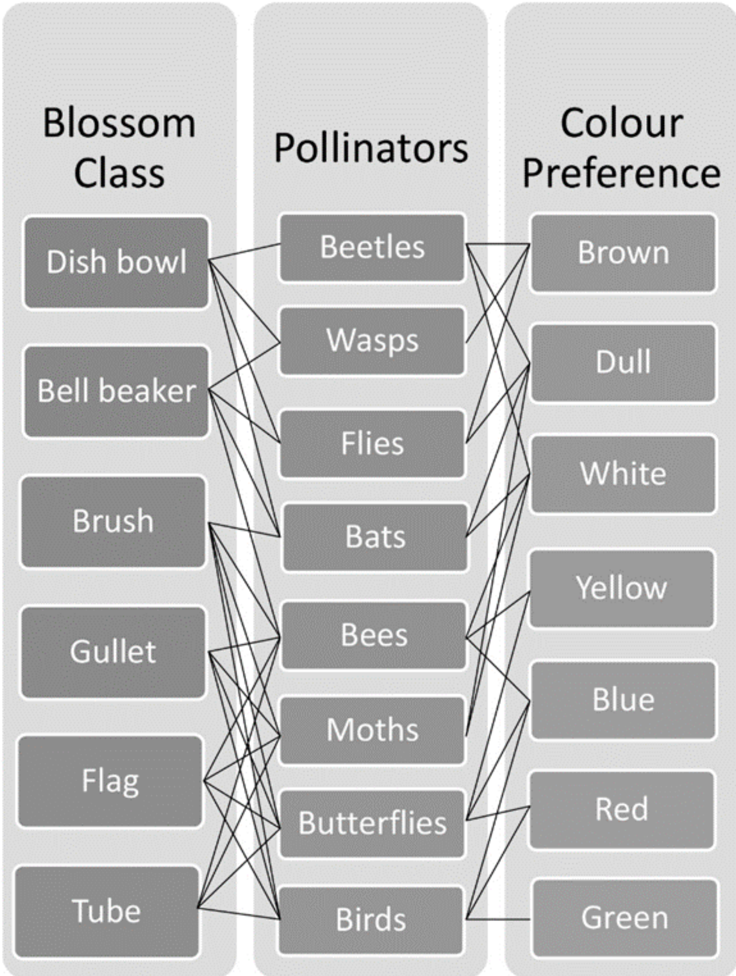

Figure 2. The pollinators and their preferred blossom class and colour.

Pollination Syndrome:

Beetle Pollination or Cantharophily

Beetles are mostly dystrophic or sometimes allotropic. Their mouthparts are short and brutal, adapted for crushing. In some groups, the mouthparts are prognathic (aligned parallel to the body's axis) (Olberg, 1951). Beetles generally need better precision when landing on blossoms, and they can handle only flowers with the most straightforward floral structures. In short, beetles are considered primitive pollinators among all insects. As a result, the blossoms they pollinate must be both olfactory and pollyphilous. Recent studies suggest that nine angiosperm families—Arecaceae, Annonaceae, Arecaceae, Cyclanthaceae, Dipterocarpaceae, Proteaceae, Magnoliaceae, Myristicaceae, and Sterculiaceae—are frequently pollinated by members of at least twenty-eight beetle families (Ulyshen et al., 2023; Muinde and Katumo, 2024).

Figure 3. A beetle visiting a *Rhododendron* flower.

Fly pollination or Myophily

Flies are generally polytropic or allotropic and sometimes dystropic. Due to their short proboscis and small size, they tend to visit flat, dish-bowl-shaped blossoms with exposed nectar and pollen, such as those of the Asteraceae and Umbelliferae, considered primitive flower traits. Dipteran pollinators are unable to carry large pollen loads (Figure 4). Larger flowers often miss the stigma and, in the case of nectar eaters, even the anthers. However, in tiny blossoms, they can be highly effective. Their large populations compensate for their low pollen-carrying capacity and limited flight range.

Additionally, flies are present almost every season throughout the year, making them reliable pollinators (Toivonen et al., 2022). As a result, fly-pollinated flowers are typically simple, regular, flat, pale, and dull-coloured (Figure 2), with prominent nectar guides and fully exposed reproductive organs, facilitating easy access to nectar. Some species develop oligo- or monophyletic relationships with flies by evolving specific rewards or trap mechanisms.

Another variation in fly pollination is sapromyophily, in which blossoms mimic the scent of decaying protein to attract carrion flies. The long-distance attractant is often paired with traps, such as a hairy interior guiding the flies toward the reproductive organs, a slippery inclined tube, or liver-like petals designed to provide landing spots for the flies. Orchids commonly exhibit sapromyophily (Lipińska et al., 2022).

Figure 4. A small amount of pollen grains adhered to the body of a Fly.

Ant-pollination or Myrmecophily

Ants are dystrophic visitors if not pollinators. They are omnipresent on almost every plant part and are often found in large numbers wherever something sweet or starchy is present. Ants primarily act as nectar thieves since they carry little to no pollen (Figure 5). However, in some cases, an entire population of ants can function as pollinators for a specific flower, facilitating vector-mediated autogamy or, to some extent, geitonogamy. For instance, *Conospermum undulatum* has adapted its pollen so that its germination rate is enhanced when carried by ants (Delnevo et al., 2020).

Figure 5. A minimal amount of pollen grains adhere to the body of an Ant.

Bee pollination or Melittophily

Bees are the most specialized pollinators, and plants are highly adapted to utilize bees for pollination. The diet of bees consists mainly of nectar and pollen. As a result, they actively collect pollen and have evolved to carry it on their bodies. There are primarily two modes of pollen carriage in bees: i) Sternotribic, where bees carry pollen on the dorsal surface of their bodies, and ii) Nototribic, where bees carry pollen on the ventral surface (Figure 6). Before entering the hive, bees brush off all the pollen using their forelegs and deposit it into the baskets on their hind legs (Faegri and Van Der Pijl, 1979). The hairs on their bodies are very dense, and these hairs develop static electricity due to air friction caused by their high-speed wing movements, becoming positively charged.

On the other hand, plants develop negative charges in their anthers and pollen grains. This charge is transferred from the roots to the flowers through the movement of electrolytes from the soil to every part of the plant. These opposite charges enable the pollen grains to adhere firmly to the bees. Witherell (1972) and Kendall and Solomon (1973) estimated that at least 15,000 pollen grains must attach to a moderate-sized bee (Kendall and Solomon, 1973). After adhering, the pollen grains become neutral or slightly positively charged. When a bee visits another flower, the positively charged pollen sticks to the negatively charged stigmatic surface.

Most bees are polytropic. Social bees, particularly worker bees, visit various flowers, ranging from tubular flowers to disc-shaped bowl flowers. They require landing spaces that match their body sizes. After landing, they crawl down into the flower toward the nectar, feed on it, and then crawl through the filaments to collect pollen. In many cases, the style of the carpel mimics the staminal filaments.

Consequently, bees sometimes (almost every alternate time) crawl up to the stigma through the style instead of the filaments (Figure 6). Giant solitary bees, such as bumblebees, are stronger than other bees and can access various types of flowers that smaller bees and other insects cannot. They can press through most floral barriers to collect nectar and pollen.

The most prominent features of bee-pollinated flowers are:

i. Zygomorphic and tubular flowers with semi-closed, intricate floral architecture.
ii. Strong and adequate landing space (e.g., horizontal petals or labellum).
iii. Bright colours, primarily white, blue, and yellow, occasionally greenish (bees can perceive wavelengths from approximately 400 to 600 nm in the visible spectrum) (Figure 2).
iv. Prominent nectar guides often appear as coloured spots or a step-like pathway leading toward the nectar.
v. A moderately strong, fresh Odor.
vi. A moderate amount of nectar is hidden inside the flower.
vii. Sex organs are either concealed or located along the path to the nectar.
viii. A large quantity of pollen in the anthers and multiple ovules per carpel.

Butterfly pollination or Psychophily

Butterflies are primarily dystrophic pollinators. Due to their long proboscis, they can access almost all blossoms to collect nectar (Figure 7). They are diurnal insects; thus, most of the flowers they visit remain open during the day. The flowers butterflies frequently visit are generally erect, tubular with flat openings, brightly coloured, and rich in nectar, although the nectar is often deeply hidden. The sex organs of these flowers are prominently displayed, allowing butterflies to mechanically assist in pollination, as they do not carry pollen themselves. Butterflies are not attracted to the scent, so these flowers usually produce a faint odouror nonexistent odour.

Figure 6. A Bee is pollinating a flower. The huge pollen load is visible on the pollen basket and the belly of the insect.

Figure 7. A butterfly is collecting nectar from a flower using its long proboscis.

Moth pollination or Phalaenophily

The pollination activity of moths is quite similar to that of butterflies, with the primary difference being that moths are nocturnal. Night-blooming species primarily rely on moths for pollination. To attract moths, these blossoms produce solid and sweet fragrances and often contain more nectar than butterflies pollinate. Such flowers are typically horizontal or pendulous, white or greyish, with well-lobed petals and deeply hidden nectar. Due to their diurnal and nocturnal habits, Lepidopterans play a significant role in pollination.

Bird pollination or Ornithophily

To be bird-pollinated, flowers must have well-displayed sex organs, a high amount of nectar hidden in a moderately sized tube, a wide mouth, and a mechanical labellum. Mostly, hummingbirds and sometimes sparrows participate in pollination. However, they mainly perform vector-mediated autogamy and geitonogamy, often accidentally, by brushing the anthers against the stigmatic surface. For example, hummingbirds are regularly found to pollinate *Costus* sp. throughout America (Kay and Grossenbacher, 2022). However, in this case, the relationship is important for the bird, not as much for the plants.

Bat pollination or Chiropterophily

Primarily nocturnal or diurnal, creamish white or drab-coloured, strong-mouthed, well-displayed big flowers with a strong sweet and fermented scent and a large amount of nectar are suitable for bat pollination. Flower bats are widespread in India and worldwide; at least 18 families have been identified as flower bat families (Fleming et al. 2009). It has been found that the crop yield of *Stenocereus queretaroensis* has improved in Mexico due to bat pollination (Tremlett et al. 2020). Apart from these, several other minor pollination syndromes exist, such as pollination by snails (Malacophily) and pollination by elephants (Elephophily) etc.

Conclusions:

Pollinators and blossoms are co-adapted for their mutual benefit and are related in several ways. For example, a dystropic, as well as a polytropic pollinator, is associated with those blossoms that are allophylic or polyphylic. The hemipterous insects are generally oligotrophic, while eutrophic species are monotropic due to their specific adaptations. These insects are typically related to hemiphylic (which, by virtue, will be oligophylic) and/or euphylic (which, by virtue, will be monophylic) (Figure 1). The relationship becomes more pronounced when a monotropic insect depends on a monophylic plant. These organisms should be considered the most advanced or evolved forms regarding their reproduction and livelihood. Therefore, these organisms are members of the climax community and become vulnerable here. If we want to conserve or protect any of them, we must protect all the other organisms linked to them. However, every organism is ultimately connected like a jigsaw puzzle. The only exception is we human beings, who began to disconnect from the ecosystem the day we discovered fire. Suppose we view evolution as auto-upgrading every living organism according to its habit, habitat, and niche by analysing data over billions of years. In that case, humans are like viruses that shut down several vital systems (read: cause the extinction of several organisms) and damage the equilibrium of the biosphere. For example, the pollinator of *Trichosanthes dioica* went extinct long ago. If farmers had not adopted a mechanical pollination process by brushing the anthers of male flowers on the stigma with their hands, parwal would not have been found on our plates.

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Chapter- 5

Advancing Agricultural Resilience: Integrating Climate-Smart Practices and Technologies

Mayukhmala Mandal and Sattam Mandal

Keywords: Adaptation, Climate-smart agriculture, Greenhouse gas emissions, Resilience, Resource efficiency, Sustainable agriculture

Abstract:

Climate-smart agriculture (CSA) focuses on practices that enhance agricultural productivity while reducing greenhouse gas emissions and improving resilience to climate change. CSA is an innovative approach designed to address the multifaceted challenges of climate change while enhancing agricultural productivity and sustainability. This strategy integrates emerging technologies, such as biotechnology and drone technology, to improve crop resilience and optimize resource use. CSA also incorporates ecosystem-based adaptation practices, such as agroforestry and wetland conservation, to bolster ecosystem services and adaptability. To scale CSA practices globally, investing in research and development, strengthening policy support, enhancing education and training, and fostering public awareness and collaboration is essential. By adopting CSA, stakeholders can significantly contribute to a more resilient, productive, and sustainable agricultural system, meeting the growing demands for food while mitigating environmental impacts. By incorporating strategies such as sustainable farming, effective water management, and soil health improvements, CSA aims to optimize resource efficiency and support adaptation and mitigation efforts in the agricultural sector.

Introduction:

Climate change is an undeniable reality supported by extensive meteorological data. GHG emissions originate from various sectors, including energy (57.8%), industry (21.7%), agriculture (17.6%), and waste management (3%). Notable sources within agriculture include rice cultivation (20.9%), soil management (13%), and crop residue incineration (2%), which together account for a total of 35.9% of emissions within the sector (Mehraj et al., 2024). Climate-smart agriculture (CSA) is an approach designed to manage landscapes-including cropland, livestock, forests, and fisheries-to increase productivity, adapt to climate change, and reduce greenhouse gas emissions. CSA addresses the dual role of agriculture as both a contributor to and a victim of climate change. It promotes resilience and sustainability through scientific research, technological innovation, and traditional knowledge. Climate change impacts, such as rising temperatures, shifting

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precipitation, and extreme weather events, challenge traditional agricultural practices, reducing soil fertility, increasing erosion, and higher emissions (Brown et al., 2019). CSA aims to counteract these effects by employing various strategies to enhance productivity and sustainability. Critical practices include improving crop varieties, adopting conservation tillage, implementing efficient water management, and integrating agroforestry (Chandra et al., 2018). These practices collectively boost productivity, conserve resources, and lower emissions.

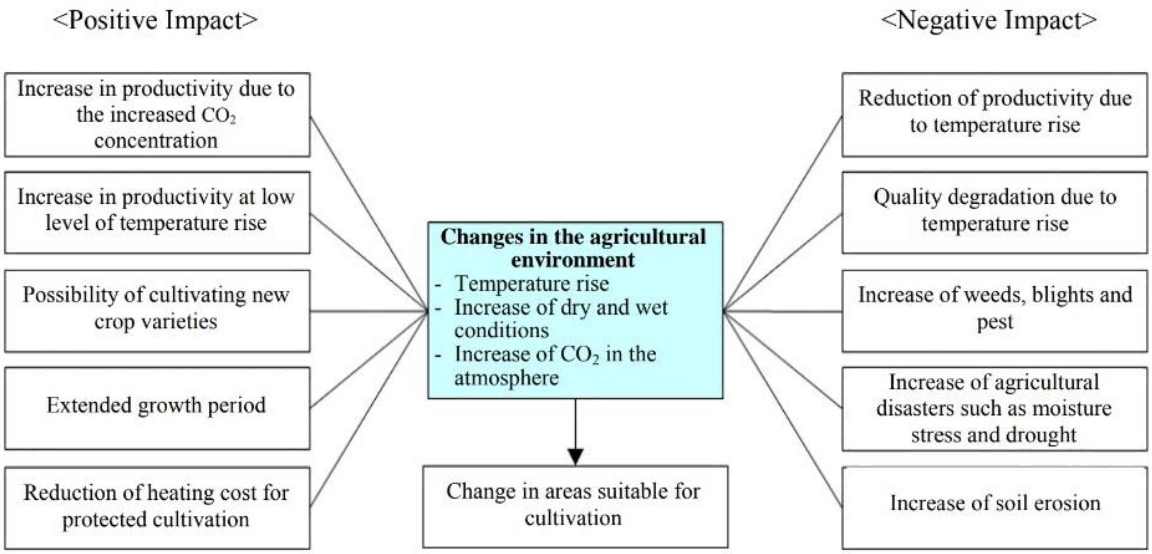
CSA emphasizes adaptation and resilience. As climate change accelerates, farmers face challenges like altered growing seasons, pest and disease pressures, and unpredictable weather. CSA helps farmers adapt by promoting soil health, improving water efficiency, and diversifying crops and livestock. For example, drought-resistant crops and advanced irrigation techniques mitigate water scarcity and improve agricultural efficiency (Campbell et al., 2020).

Mitigation is another crucial aspect of CSA. Agriculture contributes significantly to greenhouse gas emissions (Engel et al., 2016), mainly methane and nitrous oxide. CSA reduces these emissions by optimizing fertilizer use, managing manure, and adopting practices that sequester carbon in soils and vegetation. By integrating these strategies, CSA helps reduce the agricultural sector's carbon footprint and contributes to global climate efforts. CSA's flexibility allows it to be adapted to various contexts, considering local climate, soil types, and socio-economic factors (Gitz et al., 2021). This adaptability makes CSA applicable to diverse agricultural systems, from smallholder farms in developing countries to large-scale operations in industrialized nations. However, challenges such as financial constraints and limited access to technology can hinder CSA adoption, particularly in developing regions. Effective implementation requires robust policy frameworks, collaboration between governments, research institutions, and the private sector, and support mechanisms for capacity building and knowledge sharing (Candel et al., 2021).

Climate-smart agriculture (CSA) is an integrated approach designed to manage landscapes to enhance food security while addressing the challenges posed by climate change. CSA seeks to optimize the interactions between agriculture and the environment to achieve three primary goals:

1. **Increasing Productivity:** CSA aims to improve the efficiency and yield of agricultural systems, ensuring that food production meets the demands of a growing population while maintaining the ecosystem's health.
2. **Enhancing Resilience:** CSA focuses on building agricultural systems' capacity to withstand and recover from climate-related shocks and stresses, such as extreme weather events, droughts, and floods.
3. **Reducing Greenhouse Gas Emissions:** CSA promotes practices that lower agriculture's carbon footprint by reducing emissions of greenhouse gases and sequestering carbon in soil and vegetation.

Climate change poses significant challenges to agriculture, a sector crucial for food security and economic stability. The impacts of climate change on agriculture are multifaceted and profound, necessitating adopting adaptive strategies to sustain and enhance agricultural productivity.



Source: Kim, Chang-Gil and et al. (2009), p.38.

Figure 1. Potential impacts of global warming on the agricultural sector.

Impacts of Climate Change on Agriculture

1. **Altered Precipitation Patterns:** Climate change disrupts traditional precipitation patterns, leading to changes in the timing, intensity, and distribution of rainfall. Some regions may experience increased rainfall and flooding, while others may face prolonged droughts. These shifts can affect crop yields by altering soil moisture levels, which is critical for plant growth. For instance, excessive rainfall can lead to waterlogging and root damage, while insufficient rainfall can result in drought stress and reduced crop productivity.

2. **Increased Frequency of Extreme Weather Events:** Due to climate change, the frequency and intensity of extreme weather events, such as heat waves, hurricanes, and severe storms, are rising. Heat waves can cause heat stress in crops and livestock, reducing yields and productivity. Hurricanes and storms can lead to physical damage to crops and infrastructure and disrupt planting and harvesting schedules. The increased prevalence of these events heightens the vulnerability of agricultural systems.

3. **Shifts in Growing Seasons:** Climate change can alter growing seasons and affect the suitability of regions for specific crops. Warmer temperatures can lead to earlier planting and harvesting times but may also shorten growing periods for specific crops. Changes in temperature and growing conditions can shift the geographic range of agricultural zones, making it necessary for farmers to adapt their practices to new conditions.

4. **Pests and Diseases:** Warmer temperatures and changing precipitation patterns can influence the prevalence and distribution of agricultural pests and diseases. Milder winters and warmer conditions can enable pests to survive and reproduce quickly, potentially leading to

increased infestations. Similarly, changing conditions can affect plant disease spread, harming crop health and yields.

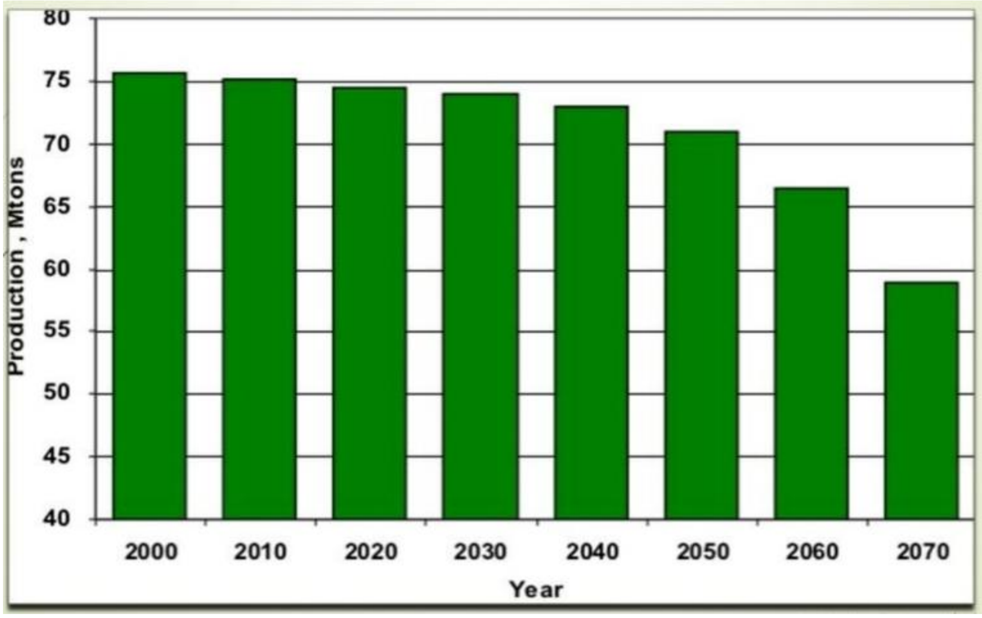


Figure 2. Potential impact of Climate Change on wheat production in India. Source: Aggrawal et al.

Need for Adaptive Strategies in Farming Practices

There is a critical need for adaptive strategies to mitigate the risks associated with climate change and ensure the resilience of agricultural systems. Key adaptive strategies include:

1. **Diversification:** Diversifying crops and livestock can reduce the risk of total crop failure or significant losses due to climate-related stresses. Farmers can spread risk and enhance their resilience to changing conditions by growing various crops or raising different types of livestock.
2. **Sustainable Water Management:** Implementing efficient water management practices, such as drip irrigation, rainwater harvesting, and soil moisture conservation techniques, can help optimize water use and reduce the impact of altered precipitation patterns. Sustainable water management is crucial in both drought-prone and flood-prone areas.
3. **Soil Conservation:** Maintaining soil health through no-till farming, cover cropping, and adding organic matter can improve soil structure and enhance its ability to retain moisture. Healthy soils are more resilient to extreme weather and can better support plant growth.
4. **Crop and Livestock Breeding:** Developing and adopting climate-resilient crop varieties should focus on traits such as drought tolerance, heat resistance, and disease resistance.
5. **Climate-Smart Agriculture (CSA):** CSA encompasses a range of practices and technologies designed to increase productivity while reducing greenhouse gas emissions and enhancing resilience to climate change. This approach integrates principles of sustainability and adaptation, promoting practices that are both economically viable and environmentally friendly (Dawn et al., 2023).

6. **Knowledge Sharing and Capacity Building:** It is essential to provide farmers with access to climate information, technical knowledge, and training on adaptive practices. Support from governments, research institutions, and extension services can facilitate the adoption of new technologies and practices (Dawn et al., 2022).
7. **Historical Agricultural Practices and Climate Adaptation:** Agricultural practices throughout history have evolved significantly in response to varying climatic conditions. Traditional farming methods were deeply intertwined with the environment, and many practices were developed to adapt to local climate patterns.

Ancient Agricultural Practices

1. **Irrigation Systems:** In ancient civilizations such as Mesopotamia, Egypt, and the Indus Valley, sophisticated irrigation systems were developed to manage water resources. The construction of canals, dikes, and reservoirs allowed farmers to control the water supply, which was crucial for cultivating crops in arid regions.
2. **Crop Rotation and Soil Management:** The ancient Greeks and Romans practised crop rotation to maintain soil fertility. By alternating crops, they reduced soil depletion and managed pests more effectively. Similarly, traditional practices in China involved using organic fertilizers and rice-fish cultivation systems, which helped maintain soil health and enhance productivity.
3. **Terracing:** In regions with hilly or mountainous terrain, such as the Andes and the Himalayas, terracing was used to create flat areas for farming. This technique prevented soil erosion and made it possible to cultivate steep slopes.

Medieval and Early Modern Agriculture

1. **Three-Field System:** The three-field system was introduced in Europe during the medieval period. This method involved rotating crops among three fields—one for winter grains, one for spring grains, and one left fallow. This practice improved soil fertility and reduced the risk of crop failure.
2. **Selective Breeding:** Farmers began selectively breeding plants and animals to enhance desirable traits. For example, in the 16th and 17th centuries, European farmers selectively bred grains and livestock to improve yields and adaptability to local conditions.
3. **Introduction of New Crops:** The Columbian Exchange brought new crops to various regions. For instance, potatoes from the Americas were introduced to Europe, and their adaptability to diverse climates helped alleviate food shortages.

19th and 20th Century Developments

1. **Mechanization and Industrialization:** The Industrial Revolution brought mechanization to agriculture by developing machines like the plough and reaper. This increased productivity but also required adaptation to new methods and technologies.
2. **Scientific Agriculture:** Advances in scientific understanding have led to improved agricultural practices. Developing synthetic fertilizers, pesticides, and high-yield crop varieties

has revolutionized farming. Soil science and climate studies have allowed for better predictions and management of agricultural practices.

3. **Climate Adaptation Strategies:** In response to climate change, farmers have increasingly adopted practices such as no-till farming, which reduces soil erosion and improves water retention. Additionally, precision agriculture technologies help optimize resource use based on real-time climate data.

Development of CSA Concepts

Climate Smart Agriculture (CSA) represents a modern approach to managing agriculture in the context of climate change. Its development reflects a shift from traditional agricultural practices to more integrated and sustainable methods. Initially, agricultural practices focused primarily on increasing productivity and efficiency without much consideration for environmental impacts or climate variability. Traditional practices often involved monocultures, heavy reliance on chemical inputs, and limited soil and water conservation measures.

Key elements of modern CSA include:

1. **Diversification and Resilience:** Implementing crop diversification and agroforestry to build resilience against climate-related shocks.
2. **Resource Efficiency:** Improving water and nutrient management through precision agriculture and sustainable practices.
3. **Soil Health:** Enhancing soil health through conservation tillage, cover cropping, and adding organic matter.
4. **Climate Information:** Utilizing climate forecasts and early warning systems to inform decision-making.

Key Milestones and International Frameworks

The evolution of Climate-Smart Agriculture (CSA) has been significantly influenced by international agreements and frameworks aimed at addressing climate change and promoting sustainable development. Key milestones include:

1. **UNFCCC (United Nations Framework Convention on Climate Change):** Established in 1992, the UNFCCC is a foundational international treaty that sets the stage for global climate action. It provides a framework for negotiating and implementing climate policies and actions among member countries.
2. **Kyoto Protocol:** Adopted in 1997, this was the first significant international agreement to reduce greenhouse gas emissions. Although primarily focused on industrialized countries, it laid the groundwork for future climate agreements.
3. **Paris Agreement:** Adopted in 2015, the Paris Agreement represents a landmark achievement in international climate policy. It aims to limit global warming to below 2°C above pre-industrial levels, with an aspirational target of 1.5°C. The agreement emphasizes the importance of mitigation and adaptation efforts, encouraging countries to develop and implement

Nationally Determined Contributions (NDCs) that include agricultural sectors and CSA practices.

4. **Sustainable Development Goals (SDGs):** Adopted in 2015 as part of the UN 2030 Agenda for Sustainable Development, the SDGs include goals directly related to agriculture and climate action. Goal 2 (Zero Hunger) and Goal 13 (Climate Action) highlight the importance of integrating CSA practices to achieve food security and climate resilience (Saha, 2023; Moitra et al., 2023; Chatterjee et al., 2023; Mukherjee et al., 2022).

5. **The Global Alliance for Climate-Smart Agriculture (GACSA):** Launched in 2014, GACSA is a platform that promotes CSA practices and supports the integration of climate-smart approaches into agricultural policies and practices worldwide.

Technological Innovations

Technological innovations in agriculture aim to improve productivity and sustainability through advanced tools and techniques. Key innovations include:

1. **Climate-Resilient Crop Varieties:** These are genetically improved crops designed to withstand various climatic stresses, such as drought, heat, and flooding. By developing and using these varieties, farmers can ensure more reliable yields and better food security in the face of climate change.

2. **Precision Agriculture:** This approach uses technology such as GPS, sensors, and data analytics to optimize field-level management for crop farming. It allows for more efficient use of water, fertilizers, and pesticides, reducing waste and environmental impact while maximizing crop productivity.

3. **ICT Tools:** Information and Communication Technologies (ICT) provide farmers with data collection, analysis, and decision-making tools. Examples include mobile apps for weather forecasts, pest and disease identification, and market prices. ICT tools can help farmers make informed decisions, manage risks, and enhance productivity.

Sustainable Agricultural Practices

Sustainable agricultural practices focus on creating farming systems that are environmentally friendly, economically viable, and socially equitable. Key components include:

1. **Crop Diversification:** Growing various crops enhances resilience, improves soil health, and reduces risks and financial instability.

2. **Conservation Tillage:** Reducing soil disturbance to preserve soil structure, reduce erosion, and improve water retention and carbon sequestration.

3. **Organic Farming:** Using natural inputs instead of synthetic chemicals to boost soil fertility, promote biodiversity, and minimize environmental impact.

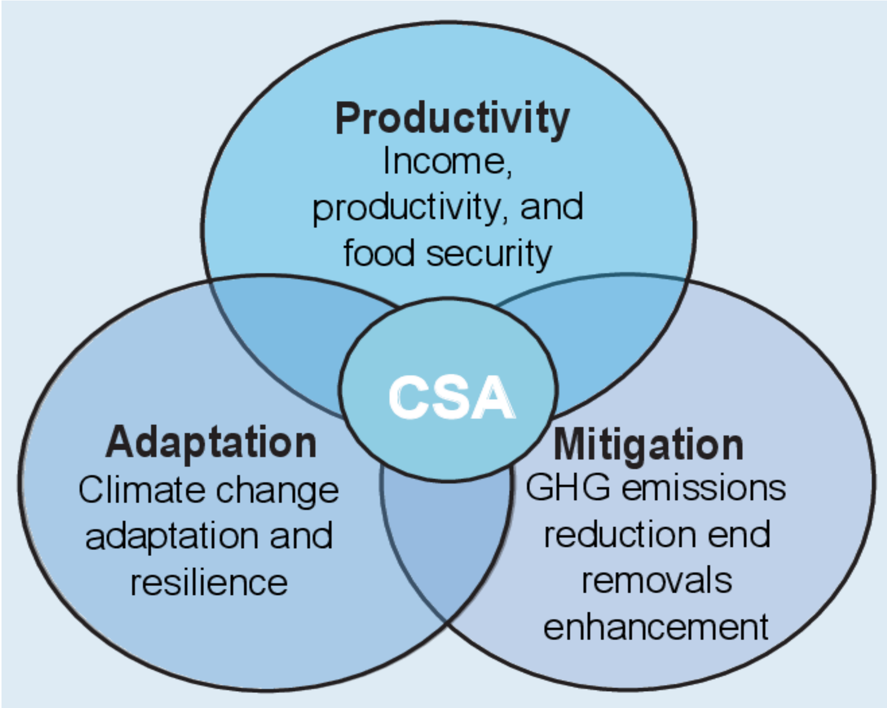


Figure 3. The Three Pillars of Climate-Smart Agriculture.

Water Management Strategies

1. **Efficient Irrigation Systems:** Advanced methods, such as drip and optimized sprinkler systems, deliver precise amounts of water to minimize water waste and improve crop yields.
2. **Rainwater Harvesting:** Collecting and storing rainwater helps reduce reliance on conventional water sources and provides a sustainable option for irrigation.
3. **Soil Moisture Conservation:** Techniques such as mulching and maintaining ground cover retain soil moisture, reduce evaporation, and improve soil health.

Soil Health and Fertility

Maintaining and improving soil health and fertility is essential for sustainable agriculture and optimal crop production. Key techniques include:

1. **Cover Cropping:** This practice involves growing specific crops (known as cover crops) when main crops are not being cultivated. Cover crops, such as legumes or grasses, help prevent soil erosion, suppress weeds, and enhance soil structure. They also contribute to nutrient cycling by adding organic matter to the soil, which improves its fertility and water-holding capacity.
2. **Composting:** Composting involves decomposing organic materials such as plant residues, animal manure, and food scraps into a nutrient-rich soil amendment. Applying compost to the soil enhances its fertility by increasing nutrient content, improving soil structure, and boosting microbial activity. Composting also reduces the need for synthetic fertilizers and helps recycle organic waste, making it a key component of sustainable soil management.

Regional Case Studies on Climate-Smart Agriculture (CSA)

Africa

In sub-Saharan Africa, CSA practices are vital for adapting to climate change. Agroforestry, such as planting *Faidherbia albida* trees in Kenya, enhances soil fertility and provides shade, thereby improving resilience to drought. In West Africa, drought-resistant crops like millet and sorghum are increasingly used to withstand arid conditions. Conservation tillage and cover crops also retain soil moisture and enhance soil structure.

Asia

In South and Southeast Asia, CSA practices address regional needs. The System of Rice Intensification (SRI) in rice cultivation boosts yields and reduces water use by up to 30%. In India, micro-irrigation systems, such as drip and sprinkler irrigation, optimize water use, critical in areas with erratic rainfall and depleting resources.

Europe and North America

Precision farming in Europe utilizes GPS and data analytics to optimize fertilizer and pesticide use, reducing waste and environmental impact. In the Netherlands, precision irrigation systems enhance water efficiency. Carbon sequestration practices, such as no-till farming and cover cropping in France, improve soil health and capture carbon dioxide.

In North America, precision farming techniques help optimize soil health, crop performance, and resource use. In the U.S., variable rate technology (VRT) enhances input application efficiency. Carbon sequestration through conservation tillage and cover crops is promoted in Canada, improving soil health and reducing greenhouse gas emissions.

Economic and Financial Constraints

1. Initial Costs of Adoption

Infrastructure Investments: Transitioning to CSA involves high initial costs for new technologies and infrastructure, which can be prohibitive for many farmers.

Risk Management: Uncertain returns from CSA practices can only deter adoption with clear evidence of financial benefits.

2. Access to Financial Support Mechanisms

Credit Availability: Limited access to affordable credit and insurance poses a barrier, as financial institutions often hesitate to lend to farmers.

Subsidies and Grants: While subsidies and grants can help, they may need to be more or better targeted, with administrative barriers limiting their effectiveness.

3. Market Access and Prices

Market Fluctuations: CSA products may face market volatility, with prices potentially not reflecting the benefits of CSA practices.

Value Chain Integration: Poor integration within value chains can restrict market access for CSA products, requiring coordinated efforts among stakeholders.

Policy Frameworks and Support Mechanisms

Subsidies: Many countries offer financial incentives to farmers to adopt climate-smart practices. For example, the U.S. Conservation Stewardship Program provides payments for practices that enhance environmental quality.

Grants: Grants are used to fund research and the implementation of CSA practices. For instance, the EU's Horizon 2020 program supports research and innovation in CSA.

Policy Examples: India's National Action Plan on Climate Change includes a National Mission for Sustainable Agriculture focusing on CSA to boost resilience and productivity.

Emerging Technologies in Climate-Smart Agriculture (CSA)

Biotechnology

Genetic Engineering and Crop Improvement: Enhances crops for drought resistance and disease resilience, reducing chemical use and stabilizing yields.

Soil Microbiome Management utilizes microbial inoculants and biofertilizers to boost soil health, enhance nutrient availability, and reduce the need for synthetic fertilizers.

Drone Technology

Precision Agriculture: Drones with sensors monitor crop health and optimize resource use by mapping field variability.

Data Collection and Analysis: Provides real-time data on crop conditions and soil moisture, facilitating accurate yield predictions and efficient resource management.

Integrative Approaches in Climate-Smart Agriculture (CSA)

Ecosystem-Based Adaptation (EbA) employs ecosystem services to help communities adapt to climate change by maintaining vital ecosystem functions, such as water regulation and soil fertility. Synergies with CSA include agroforestry, which integrates trees with crops to enhance biodiversity and soil health, and wetland conservation, which manages water flow and supports pollinators.

The Circular Economy in CSA focuses on resource efficiency by reducing waste and recycling nutrients. This includes converting agricultural waste into compost and using organic fertilizers to minimize reliance on synthetic inputs. Sustainable supply chains are emphasized through local sourcing and energy-efficient technologies.

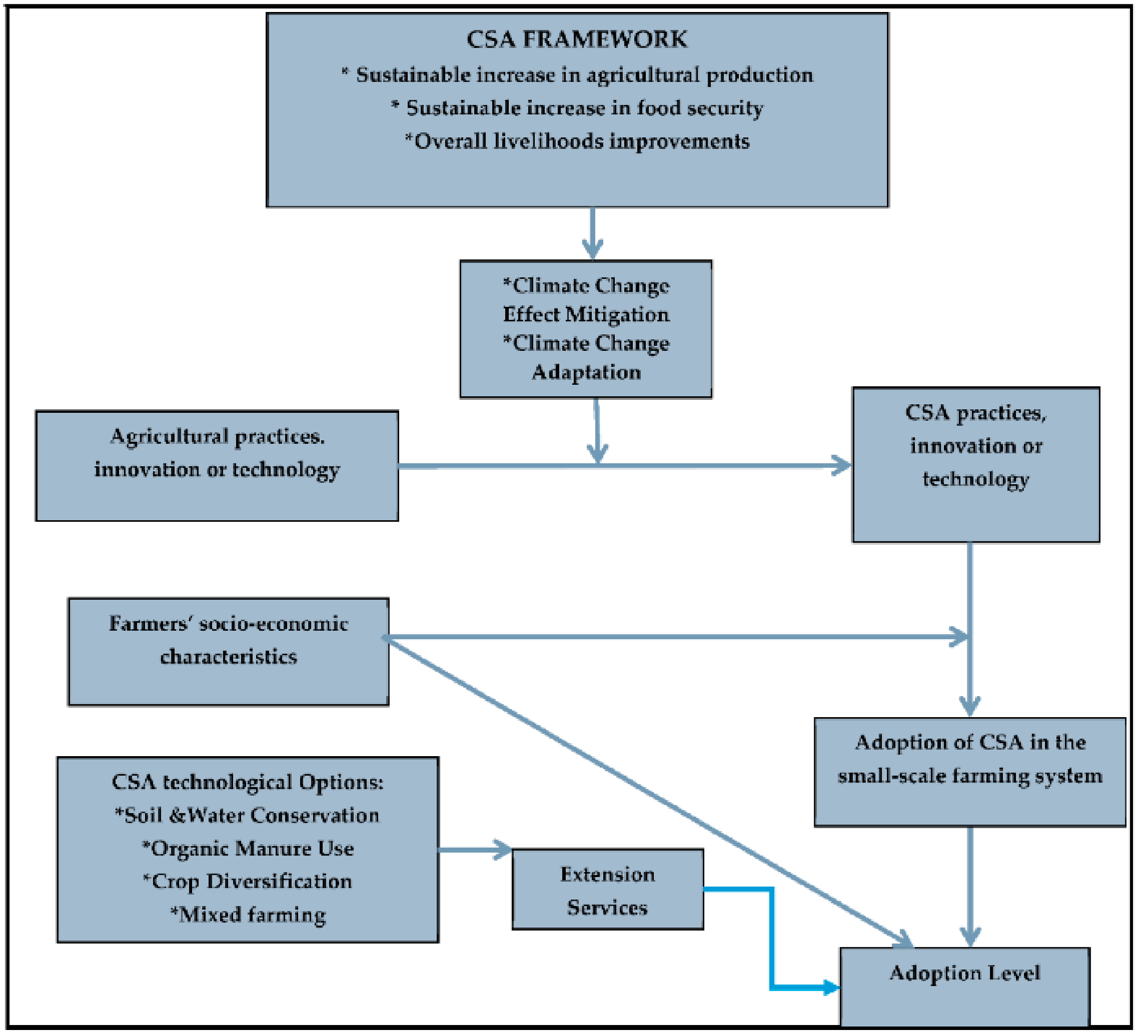


Figure 4. Conceptual framework: Adoption of Climate-Smart Agriculture (CSA) practices among small-scale farmers. Source: Adapted from Abegunde, Melusi, and Obi (2019).

Conclusion

Climate-Smart Agriculture (CSA) represents a forward-looking approach to addressing the multifaceted challenges of climate change while advancing food security and sustainable development. At its core, CSA integrates strategies to increase agricultural productivity, enhance resilience, and reduce greenhouse gas emissions, making it a pivotal element in modern agricultural practices (Brown et al., 2019). CSA boosts productivity through innovative techniques such as improved crop varieties, precision farming technologies, and advanced soil management practices. These approaches enhance crop yields and minimize losses despite climatic uncertainties (Candel et al., 2021). Farmers can achieve more efficient and resilient production systems by adopting these practices. Building resilience is another cornerstone of CSA. This involves developing crops that can withstand environmental stresses such as droughts and pests and implementing ecosystem-based adaptation strategies. This is achieved through optimizing resource use, reducing reliance on synthetic fertilizers, and implementing waste reduction and nutrient recycling strategies. Emphasizing sustainable supply chains and energy-efficient technologies further supports this goal (Engel et al., 2016). Enhancing education and training for farmers, promoting public awareness, and fostering partnerships are crucial for ensuring effective and widespread CSA implementation.

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Chapter- 6

Evaluating the Consequences of Parasitic Nematodes on Agricultural Productivity

Sujit Das, Sourav Bar, Nithar Ranjan Madhu and Sudipta Kumar Ghorai*

Keywords: Parasitic nematodes, Stylet, Agriculture, Crop plant, Taxonomy, Management

Abstract:
One of the world's biggest challenges today is providing enough food for a growing population, especially in areas like Africa where resources are few. The need for food is predicted to increase by 75% by 2050, while the global population is estimated to increase by 35%. Parasitic nematodes substantially threaten crop yields and quality, although they are often overlooked. Tiny, unsegmented roundworms known as parasitic nematodes cause significant harm to plants; they parasitize. The specialized features of certain nematodes, such as root-knot, cyst, lesion, and foliar nematodes, enable them to enter plant cells and take up nutrients, resulting in stunted development, lower yields, and, in extreme situations, plant death. Because the damage they do is typically hidden by other factors that hinder progress, their significance is frequently undervalued. A comprehensive strategy focusing on population control instead of eradication is necessary for effective nematode management. To lessen their effects on crop productivity and guarantee global food security, this chapter emphasizes the serious agricultural risks these nematodes represent and stresses the significance of integrated control strategies.

Introduction:

A significant global issue in the years ahead will be securing adequate food supplies for an increasing worldwide population. This concern is particularly urgent in resource-limited areas, such as Africa, where populations proliferate. By 2050, the global population is projected to rise by 35%, while the demand for food may jump by 75% due to economic development and shifting eating habits (World Bank (2008) World Development Report, 2008). To satisfy this demand, it

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is essential to significantly enhance resource use efficiency significantly. Improving crop yields to achieve maximum efficiency will necessitate effective management of pests and diseases, particularly as the production of specific products changes. Consequently, it is vital to thoroughly tackle all limitations in crop production, including the frequently overlooked problem of nematode restrictions.

Over 90 nations across the globe are currently utilizing indoor farming techniques to grow a diverse range of crops, such as fruits and flowers, with vegetables representing the most significant category (Hickman, 2019). The primary crops produced on indoor farms include tomatoes, cucumbers, peppers, eggplants, and strawberries, with yearly production amounts reaching 910 million kg, 400 million kg, 370 million kg, 53 million kg, and 41.5 million kg, respectively (FAO, 2017). Countries that extensively practice protected agriculture consist of China, Spain, South Korea, Turkey, Japan, Mexico, Brazil, Italy, Morocco, and Israel, holding 70% of the global area dedicated to protected agriculture, covering 5.63 million hectares. Noteworthy is the fact that the Netherlands accounts for 70% of flower exports worldwide through protected agriculture. Furthermore, China contributes to 90% of the global output of protected vegetables, while Israel effectively cultivates high-quality fruits, vegetables, and flowers in arid desert climates through indoor farming methods (Chang et al., 2013; Hickman, 2019).

Parasitic nematodes are tiny, elongated, unsegmented roundworms found in various habitats, including soil, water, and within plants and animals. They play a significant role as plant pathogens, consuming plant tissues and leading to significant harm to crops (Chitwood, 2003). These nematodes have developed unique structures like styles that enable them to penetrate plant cells and draw out nutrients. Their parasitic lifestyle causes several physiological and morphological alterations in host plants, which can lead to stunted growth, decreased yields, and, in some cases, the death of the plants (Mandal et al., 2021). Plant-parasitic nematodes are distinguished by their style and the sub-ventral and dorsal esophageal glands, essential for survival as parasites. Although they appear segmented due to multiple annulations on their cuticle, they are unsegmented, providing flexibility without causing kinks. Their bodies possess specialized organs for feeding, digestion, nerve functions and waste elimination, alongside advanced reproductive systems, but they do not have circulatory or respiratory systems (Mandal et al., 2021; Kundu, 2022). Many nematode species are also called "farmer's best friends" because they can eliminate insect pests (Shah and Mahamood, 2017). Crop damage caused by nematodes often goes unnoticed, as it can be obscured by other factors that impair plant growth (Schmitt and Sipes, 2004). To effectively manage nematodes, a comprehensive strategy is necessary. Since total eradication is unattainable, the goal is to regulate their population and maintain their numbers below damaging levels (Schmitt and Sipes, 2004). Approaches include planting resistant varieties of crops, practising crop rotation, adding soil amendments, and applying pesticides. In some cases, soil solarization may also be beneficial (Schmitt and Sipes, 1998).

Agricultural productivity is vital in ensuring food security worldwide but often faces threats from various biological and environmental factors. One of the significant, frequently overlooked challenges is posed by parasitic nematodes. These small, soil-dwelling worms can inflict serious harm on crops, resulting in reduced yields, poorer quality of produce, and increased production costs. Despite their tiny size, the damage they cause can be extensive, impacting not only individual plants but also entire agricultural systems.

Biology and Ecology of plant parasitic nematodes:

Classification:

Plant-parasitic nematodes are classified based on their taxonomic ranks and the morphological characteristics that define different families and orders. According to the classification system provided by De Ley and Blaxter in 2002, it is used, which integrates molecular phylogenetic results with morphological analyses. The major nematode orders containing plant-parasitic species are Rhabditida, Dorylaimida, and Triplonchida. Below is the detailed classification (Mekete et al., 2012):

Order: Rhabditida

Infraorder: Tylenchomorpha

1. Superfamily: Aphelenchoidea

- Family: Aphelenchidae
- Family: Aphelenchoididae
- Family: Paraphelenchidae

2. Superfamily: Criconematoidea

- Family: Criconematidae
- Family: Hemicycliophoridae
- Family: Tylenchulidae

3. Superfamily: Myenchoidea

- Family: Myenchidae

4. Superfamily: Sphaerularioidea

- Family: Allantonematidae
- Family: Anguinidae
- Family: Iotonchiidae
- Family: Neotylenchidae
- Family: Parasitylenchidae
- Family: Sphaerulariidae
- Family: Sychnotylenchidae

5. Superfamily: Tylenchoidea

- Family: Atylenchidae
- Family: Belonolaimidae

- Family: Dolichodoridae
- Family: Ecphyadophoridae
- Family: Heteroderidae
- Family: Hoplolaimidae
- Family: Meloidogynidae
- Family: Pratylenchidae
- Family: Psilenchidae
- Family: Telotylenchidae
- Family: Tylenchidae
- Family: Tylodoridae

Order: Dorylaimida

1. Superfamily: Dorylaimoidea

- Family: Dorylaimidae
- Family: Longidoridae
- Family: Xiphinematidae
- Family: Trichodoridae

Order: Triplonchida

Suborder: Diphtherophorina

1. Superfamily: Diphtherophoroidea

- Family: Diphtherophoridae
- Family: Trichodoridae

Suborder: Tobrilina

1. Superfamily: Prismatolaimoidea

- Family: Prismatolaimidae

2. Superfamily: Tobriloidea

- Family: Pandolaimidae
- Family: Rhabdodemaniidae
- Family: Tobrilidae
- Family: Triodontolaimidae

Suborder: Triplonchida

- Family: Bastianiidae
- Family: Odontolaimidae

Suborder: Tripylina

3. Superfamily: Tripyloidea

- Family: Onchulidae
- Family: Tripylidae

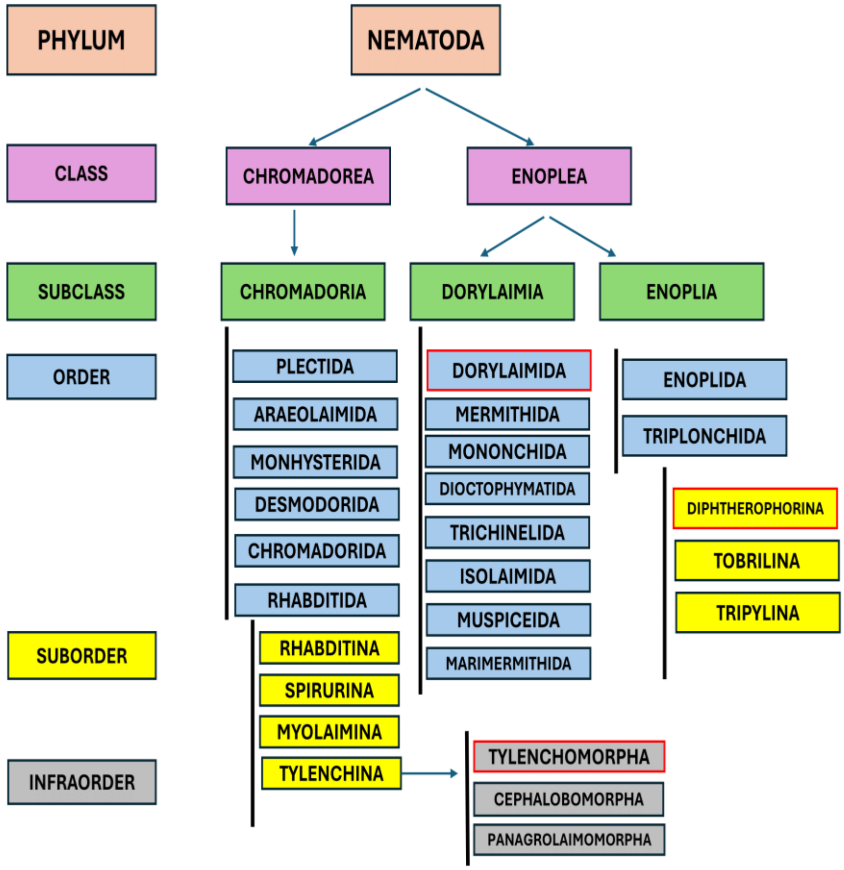

Figure 1. Taxonomic classification of Parasitic Nematode (De Ley and Blaxter, 2002)

Notable Genera and Species:

- Root-Knot Nematodes (*Meloidogyne* spp.)

These nematodes are considered some of the most harmful parasites affecting plants, as they create root galls that hinder the plant's capacity to take up water and nutrients. Species like *Meloidogyne incognita* and *Meloidogyne javanica* are prevalent and target a range of crops (Subedi et al., 2020).

- Cyst Nematodes (*Heterodera* spp. and *Globodera* spp.)

Cyst nematodes create cysts on plant roots, which can survive in the soil for many years, complicating management efforts. *Heterodera glycines* (the soybean cyst nematode) and *Globodera rostochiensis* (the potato cyst nematode) are notable threats to their respective crops (Ibrahim et al., 2017).

- Lesion Nematodes (*Pratylenchus spp.*)

Lesion nematodes infiltrate root tissues, resulting in necrotic lesions that diminish the plant's functionality. Common species such as *Pratylenchus penetrans* and *Pratylenchus neglectus* impact various crops (Jones and Fosu-Nyarko, 2014).

- Foliar Nematodes (*Aphelenchoides spp.)*

These nematodes attack the aerial parts of plants, such as leaves and buds, leading to deformation and tissue. *Aphelenchoides fragariae* is particularly known for its impact on strawberries and various ornamental species (Handoo et al., 2020).

1.3. Life Cycle and Reproduction:

Nematodes experience a life cycle consisting of six distinct stages: an egg stage, four juvenile stages, and an adult stage. The first four stages are deemed immature and categorized as juvenile stages (Wharton and Wharton, 1986). This life cycle is straightforward. Generally, female nematodes deposit their eggs in soil or within plant tissues, either individually or in clusters. These eggs are oval and have protective layers, including an outer coating, an inner lipid layer, and a valid shell. The first moult occurs within the egg, leading to the second-stage juvenile (J2) emergence as it breaks free from the eggshell. These larvae can either stay within the host throughout their life or migrate away from the feeding areas. In terms of appearance, the larvae closely resemble adult nematodes. Adult nematodes predominantly inhabit the soil, feeding on newly developed roots (Maggenti and Allen, 1959). A depiction of the nematode life cycle is presented in Figure 1.

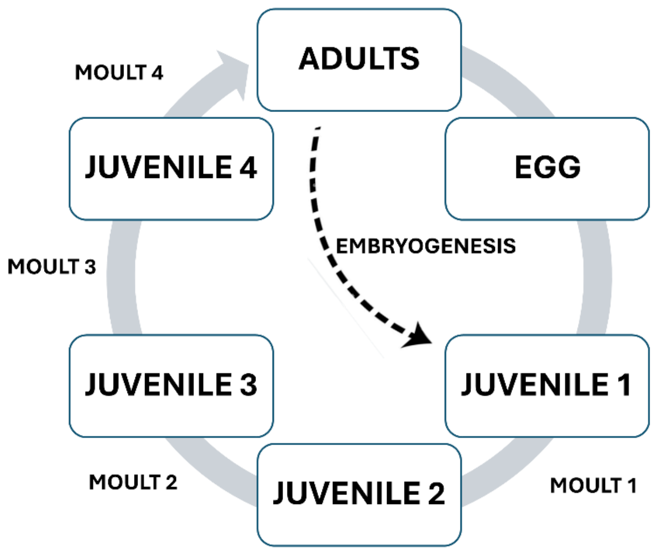

Figure 2. Life cycle of plant parasitic nematodes (Mandal et al., 2021).

Host range and Specificity:

Cyst Nematode (*Heterodera* spp.)

Distribution:

Cyst nematodes, such as *H. filipjevi* and *H. latipons*, have been identified in various locations, including North Africa, Algeria, several European nations, and the Mediterranean region (Smaha et al., 2019).

Host Range:

The genus Heterodera includes 70 identified species, among which 12 species from the *H. avenae* are especially detrimental economically. These nematodes mainly target crops such as potatoes, soybeans, oats, wheat, and barley (Bohlmann and Sobczak, 2014).

Symptoms:

Intense populations of cyst nematodes can lead to poor growth, wilting, and yellowing of the leaves, resulting in notable reductions in crop yield. After several weeks of parasitism, adult females can be observed attached to the roots of the host plants (Mitiku, 2018; Lilley et al., **2005).**

Life Cycle Duration:

The life cycle of cyst nematodes spans up to 55 days, and they reproduce through an amphimictic method (Turner and Subbotin, 2006).

Feeding Habit:

Juvenile cyst nematodes are migratory endoparasites that penetrate plants' vascular tissue and consume their sap (Mitiku, 2018).

Root Rot Nematode (*Hirschmanniella* spp.)

Distribution:

Hirschmanniella miticausa has been found in Papua New Guinea and the Islands (CABI,2019). These stationary nematodes are referred to as such due to the knot-like galls they create on the roots of affected plants (Subedi et al., 2020).

Host Range:

The genus Hirschmanniella consists of 24 species, with 12 of them parasitizing rice. They also infest other crops, including cotton, sugarcane, and maize (Regmi and Desaeger, 2020).

Symptoms:

Symptoms above the ground are not prominently visible, although infected plants might show signs of chlorosis and hindered growth. *H. oryzae* penetrates through lateral roots and moves into the aerenchyma, leading to tissue death. Additionally, subsequent infections by other microorganisms can cause browning of the rice roots (Bauters et al., 2014).

Life Cycle Duration:

Under optimal conditions, the life cycle of these nematodes can last up to 30 days and involves sexual reproduction. They display migratory endoparasitic behaviour (Regmi and Desaeger, 2020).

Sting Nematode (*Belonolaimus* spp.)

Distribution:

From Texas to Virginia, Belonolaimus longicaudatus was initially documented in the southeastern United States, typically along the Gulf of Mexico and the Atlantic coasts. This species has also been observed in Australia, Venezuela, and Brazil (Gozel et al., 2006).

Host Range:

The host plants of *B. longicaudatus* include corn, turfgrasses, peanuts, citrus fruits, strawberries, and various root vegetables (Abu-Gharbieh and Perry, 1970).

Symptoms:

High populations of *B. longicaudatus* can damage root areas, hindering the uptake of water and nutrients. This results in stunted plant growth, wilting, leaf yellowing (chlorosis), and, in extreme cases, the death of the plant (Mandal et al., 2021).

Life Cycle Duration:

This ectoparasitic nematode can have a life cycle lasting up to 28 days, with reproduction taking place through an amphimictic process (Mandal et al., 2021).

Citrus Nematode (*Tylenchulus* spp.)

Distribution:

Tylenchulus semipenetrans is found globally and frequently in citrus plants. This nematode mainly targets species from the Rutaceae family, particularly *Poncirus trifoliata* and its hybrids. Other hosts include grapes, olives, and persimmons (Inserra et al., 1994).

Symptoms:

T. semipenetrans can lead to economic losses in yield ranging from 10 to 30%. Visible signs above the ground include stunted plant growth, yellowing leaves, and decreased fruit production. The roots of infected plants become thicker than those of healthy plants, resulting in a gradual decline in the health of citrus crops (Verdejo-Lucas and McKenry, 2004).

Duration of Life Cycle:

Citrus nematodes exhibit a semi-endoparasitic feeding behavior. Their life cycle spans 4 to 8 weeks, with reproduction occurring via amphimictic, meiotic, and parthenogenetic methods (Shokoohi and Duncan, 2018).

Seed Gall Nematode/Ear Cockle Nematode (*Anguina* spp.)

Distribution:

Seed gall nematodes are located in various areas including West Africa, North Africa, Australia, Brazil, China, India, Turkey, France, Italy, Iraq, and the USA (Tulek et al., 2015). The *Anguina* genus consists of 11 different species (Powers et al., 2001).

Host Range:

The primary hosts for these nematodes are wheat, rye, and barley. Wheat can experience 52% to 100%, while rye losses are typically between 50% and 65% (Mukhtar et al., 2018).

Symptoms:

Second-stage juveniles infiltrate wheat seedlings in wet soil and feed on them externally. They subsequently invade the floral primordia internally. Symptoms of infestation include leaf rolling and curling, the formation of small blisters on leaves, and distortion of stems (Ozberk et al., 2011; Mukhtar et al., 2018; Ami and Taher, 2013).

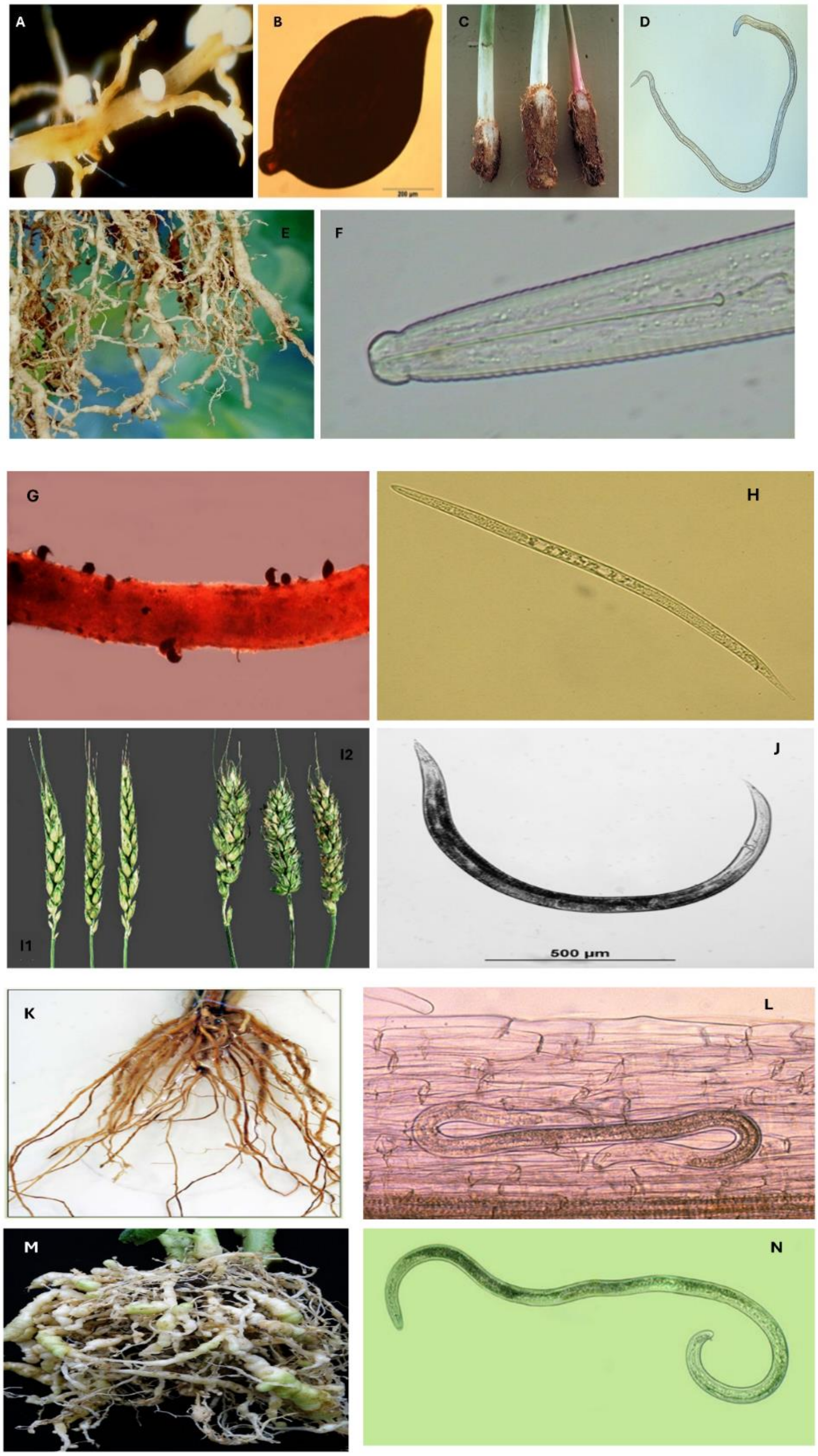

Figure 3. A, B- Cyst nematode and its Symptoms in the host plant. C, D- Root rot nematode and its symptoms in the host plant. E, F- Sting nematode and its effect on the host plant. G, H- Citrus nematode and its characteristic effect on the host plant. I (1, 2), J- Seed gall nematode and its effect on wheat. K, L- Lesion Nematode and the root affected by it. M, N- Knot formation in the root by Root-knot nematode. Picture Courtesy: (Google.com)

Lesion Nematode (Pratylenchus spp.)

Distribution:

Root lesion nematodes (RLNs), which belong to the genus Pratylenchus, are distributed globally and comprise approximately 97 recognized species.

Host Range:

Key hosts for RLNs include cereals, legumes, vegetables, fruits, ornamental plants, coffee, and peanuts. In temperate regions, twelve species are known to inflict significant damage, with eight being significantly detrimental to cereal crops (Fosu-Nyarko and Jones, 2016).

Symptoms:

Common symptoms in affected plants such as potatoes include yellowing leaves, stunted growth, and decay in roots and tubers (Esteves et al., 2015).

Duration of Life Cycle:

RLNs are migratory endoparasites whose life cycles range from 3 to 9 weeks and are influenced by specific species and environmental factors. For example, P. penetrans in red clover completes its cycle in 9 weeks. They reproduce through parthenogenesis and can endure harsh conditions in the soil for extended periods due to anhydrobiosis, making it possible for Pratylenchus spp. to survive for many years (Jones and Fosu-Nyarko, 2014).

Root Knot Nematode (*Meloidogyne* spp.)

Distribution:

Root-knot nematodes are found worldwide, with 98 identified species that cause about 5% of global economic losses (Khanal et al., 2016).

Host Range:

Their hosts comprise cover crops, fruit trees, weeds, ornamental plants, and agronomic crops (Khanal et al., 2016).

Symptoms:

These nematodes induce the development of galls or knots due to the swelling of root cells. Additional symptoms can include wilting, yellowing of leaves, nutrient deficiencies, and stunted growth (Ralmi et al., 2016).

Duration of Life Cycle:

Root-knot nematodes can be either migratory or sedentary endoparasites. They penetrate root zones to feed and have a life cycle that spans approximately 3-4 weeks under optimal conditions (Khan, 2015).

Table 1. Plant Parasitic Nematodes and their host plants (Phani et al., 2021)

Crop	Nematode species	Country	Reference
Tomato	*Meloidogyne hapla*	Canada	Belair and Tremblay (1995)
Tomato	*Meloidogyne incognita*	China	Tingting et al. (2005)
Tomato	*Nacobbus aberrans*	Argentina	Vovlas et al. (2007)
Tomato	*Meloidogyne javanica*	Cyprus	Philis (1994)

Tomato	*Meloidogyne javanica*	Ethiopia	Beyan et al. (2019)
Tomato	*Meloidogyne javanica*	Greece	Tzortzakakis and Petsas (2003)
Tomato	*Meloidogyne incognita, M. arenaria,* *M. javanica*	India	Ramasamy and Ravishankar (2018)
Tomato	*Meloidogyne incognita, M. javanica, M. hapla*	Italy	Calabretta and Privitera (1985)
Tomato	*Meloidogyne* spp.	Italy	Fiume and Parisi (1995)
Tomato	*Meloidogyne* spp.	Italy	Assenza et al. (2000)
Tomato	*Meloidogyne* spp.	Italy	Lamberti et al. (2003)
Tomato	*Meloidogyne* spp.	Italy	Polizzi et al. (2004)
Tomato	*Meloidogyne incognita, M. javanica*	Italy	Minuto et al. (2006)
Tomato	*Meloidogyne incognita*	Italy	D'Errico et al. (2016)
Tomato	*Meloidogyne javanica*	Jordan	Muhammad et al. (1991)
Tomato	*Meloidogyne incognita*	Netherlands	Cools and Stolk (1984)
Tomato	*Meloidogyne* spp.	Portugal	Silveira and Gorges (1984)
Tomato	*Meloidogyne incognita, M. javanica, M. arenaria*	Russia	Khurramov (1990)
Tomato	*Meloidogyne incognita*	Saudi Arabia	Almaghrabi et al. (2012)
Tomato	*Meloidogyne* spp.	Spain	Ojinaga (2018)
Tomato	*Meloidogyne javanica*	Spain	Sorribas et al. (2003)
Tomato	*Meloidogyne incognita, M. javanica*	Syria	Toumi et al. (2014)
Tomato	*Meloidogyne incognita, M. javanica*	Turkey	Yucel et al. (2007)
Tomato	*Meloidogyne incognita*	Turkey	Kaskavalci (2007)
Tomato	*Meloidogyne ethiopica* (reclassified as *M. luci)*	Turkey	Aydinli et al. (2013); Geriˇ c Stare et al. (2017)
Tomato, cucumber	*Meloidogyne* spp.	Greece	Giannakou and Panopoulou (2019)
Tomato, cucumber	*Meloidogyne* spp.	Albania	Pertena et al. (2005)
Tomato, cucumber	*Meloidogyne* spp.	Greece	Giannakou and Anastasiadis (2005)
Tomato, cucumber	*Meloidogyne incognita, M. javanica*	Brazil	Charchar and Aragao (2005)
Tomato, cucumber	*Meloidogyne incognita*	Russia	Lashkova and Danilov (1982)
Tomato, cucumber	*Meloidogyne* spp.	Russia	Yarkulov (2000)

Tomato, cucumber	*Meloidogyne incognita*	Spain	Gine and Sorribas (2017)
Tomato, cucumber	*Meloidogyne arenaria, M. incognita*	Uzbekistan	Rizaeva (1983)
Tomato, cucumber	*Meloidogyne enterolobii*	Switzerland	Kiewnick et al. (2008)
Tomato, cucumber	*Meloidogyne javanica*	Russia	Trusevich (2004)
Tomato, cucumber	*Meloidogyne* spp.	Bosnia and Herzegovina	Kohnic et al. (2006)
Tomato, cucumber, chili, bell pepper	*Meloidogyne incognita, M. javanica, Helicotylenchus dihystera, Hoplolaimus columbus, Pratylenchus penetrans, Radopholus similis, Tylenchorhynchus claytoni, Xiphinema* spp.	Pakistan	Anwar et al. (2013)
Cucumber	*Meloidogyne* spp.	China	Xiao et al. (2006)
Cucumber	*Meloidogyne* spp.	Egypt	El-Haddad et al. (2003)
Cucumber	*Meloidogyne incognita*	Egypt	El-Rab (2000)
Cucumber	*Meloidogyne incognita*	Egypt	Amin et al. (2014)
Cucumber	*Meloidogyne* spp.	Brazil	Kohnic et al. (2006)
Cucumber	*Meloidogyne* spp.	Hungary	Toth (2019)
Cucumber	*Meloidogyne* spp.	Russia	Dobrokhotov (2000)
Cucumber	*Meloidogyne* spp.	Russia	Bedin and Tokarev (2004)
Cucumber	*Meloidogyne incognita*	Spain	Gine et al. (2017)
Cucumber	*Plant-Parasitic nematodes (unspecified)*	Spain	Echevarría et al. (2004)
Cucumber	*Plant-Parasiticnematodes (unspecified)*	Turkey	Engindeniz and Engindeniz (2006)
Tomato, lettuce	*Meloidogyne javanica*	Spain	Verdejo-Lucas et al. (2003)
Tomato, lettuce	*Meloidogyne* spp.	Germany	Graf et al. (2001)
Tomato, bell pepper, eggplant, cucurbits (melon, cucumber, courgette), lettuce, beet, bean, radish,	*Meloidogyne* spp., *Heterodera carotae, H. cruciferae, D. dipsaci, Pratylenchus* spp., *Tylenchorhynchus* spp.	France	Djian-Caporalino (2012)

spinach, basil, fennel, celery, strawberry			
Tomato, cucumber, pepper, eggplant, beans, banana, flower crops	*Meloidogyne* spp.	Mediterranean region (various)	Hanafi and Papasolomontos (1999)
Tomato, beans, eggplant, zucchini	*Meloidogyne javanica, M. incognita*	Morocco	Janati et al. (2018)
Tomato, cucumber, eggplant, sweet pepper, green bean, squash	*Meloidogyne* spp., *Aphelenchoides* spp., *Tylenchorhynchus* spp., *Ditylenchus* spp., *Pratylenchus* spp., *Subanguina* spp., *Trichodorus* spp., *Hemicriconemoides* spp., *Paratylenchus* spp., *Helicotylenchus* spp., *Longidorus* spp., *Merlinius* spp.	Saudi Arabia	Almohithef et al. (2020)
Tomato, bell pepper, cucumber, tobacco	*Meloidogyne incognita*	USA	Kloepper et al. (2004)
Sweet pepper	*Meloidogyne incognita*	Spain	Ros et al. (2006)
Sweet pepper	*Meloidogyne incognita*	Spain	Guerrero et al. (2005)
Pepper	*Meloidogyne incognita, M. javanica*	Italy	Cartia et al. (1989)
Pepper	*Meloidogyne* spp. *(mixed population of M. incognita, M. javanica, M. arenaria)*	Turkey	Özarslandan et al. (2019)
Sweet pepper, carnation, cauliflower, tomato, eggplant, cucurbits	*Meloidogyne incognita, Helicotylenchus dihystera, Rotylenchulus reniformis, Pratylenchus* spp.	India	Chandel et al. (2010)
Cucumber, nightshade, tomato, melon, eggplant, pepper	*Meloidogyne arenaria, M. ethiopica, M. javanica, M. incognita*	Turkey	Aydinli and Mennan (2016)

Sweet pea	*Pratylenchus* spp.	Germany	Schreiner (1986)
French bean, cucurbits, tomato, crucifers, potato, capsicum	*Meloidogyne* spp., *Pratylenchus* spp., *Helicotylenchus* spp., *Mesocriconema* spp., *Tylenchorhynchus* spp., *Hoplolaimus* spp.	India	Singh and Khanna (2015)
Eggplant	*Meloidogyne* spp.	Italy	Cartia et al. (1996)
Eggplant	*Meloidogyne incognita*	Turkey	Çürük (2009)
Capsicum, tomato, chilli, okra, gherkin, muskmelon, watermelon, carnation, rose, gerbera, anthurium	*Meloidogyne incognita*, *M. javanica*, *Rotylenchulus reniformis*	India	Rao et al. (2015)
Cucumber, chilli, bell pepper, tomato	*Meloidogyne incognita*, *Pratylenchus* spp., *Rotylenchulus* spp., *Hoplolaimus* spp., *Helicotylenchus* spp., *Tylenchorhynchus* spp., *Ditylenchus* spp.	India	Patil et al. (2016)
Melon	*Meloidogyne arenaria*	Korea	Kim (2001)
Strawberry	*Xiphinema mediterraneum*, *Pratylenchus penetrans*, *Paraphelenchus pseudoparietinus*, *Helicotylenchus multicinctus*, *Aphelenchoides subtenuis*	Bulgaria	Nikolova et al. (1976)
Lettuce	*Paratylenchus* spp.	Belgium	Claerbout (2020)
Grape	*Pratylenchus* spp., *Tylenchorhynchus* spp., *Rotylenchulus* spp., *Tylenchus* spp.	India	Askary et al. (2018)
Sunflower	*Meloidogyne incognita*	Egypt	Rashad et al. (2011)
Cabbage	*Meloidogyne incognita*	India	Rana et al. (2018)
Strawberry	*Meloidogyne* spp., *Ditylenchus* spp.	Italy	Manzali (1994)
Sweet basil	*Aphelenchoides ritzemabosi*	Italy	Vovlas et al. (2005)
Soybean	*Rotylenchulus reniformis*	USA	Rodriguez-Kabana et al. (2003)

Tomato, spinach, strawberry, melon	*Meloidogyne* spp.	Japan	Tanaka et al. (2000)
Tomato, pepper	*Meloidogyne spp.*	Greece	Prophetou-Athanasiadou et al. (2002)
Capsicum, tomato, cucumber, cabbage, carrot	*Meloidogyne spp.*	Hungary	Dabaj et al. (1994)
Capsicum, melon, tomato, lettuce	*Meloidogyne javanica*	Spain	Cenis (1984)
Greenhouse plants in botanical gardens	*Aphelenchoides fragariae, Ditylenchus destructor, D. dipsaci, Belondira paraclava, Helicotylenchus dehystera, Hemicycliophora parvana, Heterodera fici, Longidorus elongatus, Macroposthonia annulata, Paratrichodorus acutus, Meloidogyne incognita, Paratylenchus nanus, Pratylenchus crenatus, P. penetrans, Rotylenchus robustus, Tylenchorhynchus claytoni, T. dubius, Xiphinema americanum*	Ukraine	Gubin and Sigareva (2014)
Watermelon, cucumber, melon, tomato, eggplant	*Meloidogyne* spp.	Japan	Oda (1993)
Sweet pepper, tomato, cucumber, courgette, watermelon, eggplant, muskmelon	*Meloidogyne* spp.	Spain	Talavera et al. (2012)
Tomato, eggplant, carrot, radish, cucurbits	*Meloidogyne incognita, M. javanica, R. reniformis,*	India	Gowda et al. (2017)

	Hoplolaimus spp., *Tylenchorhynchus* spp., *Helicotylenchus* spp.		
Rose, carrot, spinach, chrysanthemum, Broccoli, spring onion, cabbage, Chinese leek	*Aphelenchoides* spp., *Criconemella* spp., *Helicotylenchus* spp., *Meloidogyne* spp., *Paratrichodorus* spp., *Paratylenchus* spp., *Rotylenchulus* spp.	Japan	Yamamoto and Toida (1995)
Capsicum, cucumber, tomato, carnation, gerbera, rose	*Meloidogyne* spp., *R. reniformis*, *Pratylenchus* spp., *Aphelenchoides fragariae*, *Radopholus similis*, *Ditylenchus dipsaci*	India	Sharma et al. (2009)
Tomato, cucumber, pepper, carnation, gerbera, rose	*Meloidogyne* spp., *R. reniformis*, *Pratylenchus* spp., *Hoplolaimus* spp., *Tylenchorhynchus* spp., *Helicotylenchus* spp.	India	Sabir and Walia (2017)
Tomato, cucumber, eggplant, melon, squash, beans, lettuce	*Meloidogyne* spp., *Radopholus* spp., *Aphelenchoides* spp., *Ditylenchus* spp., *Pratylenchus* spp.	USA	Noling and Rich (2010)
Cut flowers and ornamentals	*Macroposthonia curvata*, *Xiphinema diversicaudatum*, *Ditylenchus dipsaci*, *Meloidogyne incognita*, *Aphelenchoides ritzemabosi*	Bulgaria	Choleva (1982)
Rose, gypsophila	*Mesocriconema sphaerocephaloides*, *Longidorus laevicapitatus*, *Paratylenchus obtusicaudatus*, *Nanidorus minor*	Ethiopia	Meressa et al. (2015)
Anthurium	*Radopholus similis*	Hawaii	Aragaki et al. (1984)
Carnation, gerbera	*Dazomet, chlorpyriphos, carbosulfan, carbofuran, Paecilomyces lilacinus*	India	Nagesh and Parvatha Reddy (2005)

	(= Purpureocillium lilacinum), Pochonia chlamydosporia, neem cake		
Carnation	*Pochonia chlamydosporia*	India	Rao and Shaylaja (2003)
Rose	*Heterodera daverti*	Italy	Lung et al. (1997)
Rose	*Meloidogyne* spp.	Kenya	Oloo et al. (2009)

Mechanism of parasitism:

Plant parasitic nematodes (PPNs) have complex infection processes that enable them to colonize and exploit plant hosts effectively. The infection process generally involves the following stages:

Attraction to Host Plants:

Actively growing roots generate different gradients of both volatile and non-volatile, such as amino acids, ions, pH levels, and CO2. Nematodes have specialized chemosensory structures called amphids that they use to locate these roots by sensing these gradients. This capacity to move toward root stimuli enhances their chances of encountering a host and reduces the duration without food (Perry, 1997). It is widely recognized that the cyst and root-knot nematodes' second-stage juveniles (J2) are drawn to the root tip, their favoured invasion site. Nonetheless, the elements that serve as "local attractants" have not been determined (Reynolds et al., 2011). These nematodes may react to an electrical potential gradient present in the root tip's elongation zone. The relative importance of electrical and chemical attractants in directing nematodes to the root tip remains unclear. Furthermore, the elevated temperature in the root elongation zone might also influence nematode perception.

Penetration and Feeding:

Nematodes can infiltrate plant roots by utilising their stylet, a structure resembling a needle, or by exploiting natural apertures like root tips or hairs. Invading host roots, sedentary endoparasitic nematodes create feeding sites inside the root tissue and feed internally. Recent and ongoing studies on the feeding habits of endoparasitic species have mainly concentrated on worms with cysts and knots in their roots. But other nematodes, such as Nacobbus, also produce feeding sites that serve as sinks for nutrients (Manzanilla-López et al. 2002). These nematodes could be studied more and more in the future, especially with the development of comparative genomics.

Both cyst and root-knot nematodes emit cell wall-degrading enzymes through their stylets, facilitating their movement by weakening or disintegrating plant cell walls. The subventral glands generate these enzymes. Root-knot nematodes also produce xylanase and polygalacturonase, in addition to the identified enzymes cellulases and pectate lyases (Davis et al., 2000; Gheysen and Jones, 2006).

Migration:

Nematodes travel across cells in search of their preferred feeding places after entry. Certain nematodes, such as *Meloidogyne spp*., the root-knot nematode, can pass through plant cells and seriously harm the cells. Only the J2 and adult males of cyst and root-knot nematodes migrate. However, in species such as Nacobbus, only the mature female remains static; all juvenile stages, the male and the immature vermiform female, are migratory. Pratylenchus and Radopholus are two examples of migratory endoparasitic nematodes that infiltrate plant hosts through mobile stages before becoming sessile. Instead of creating permanent feeding sites inside the plant, these nematodes move about, feed on several cells, and seriously harm the plant's tissue (Port, 1980).

Moulting:

The effects of the principal moulting hormone in insects, 20-hydroxyecdysone (20E), on *Meloidogyne javanica* were studied by Soriano et al. (2004). When exogenous 20E was applied, it caused J2 to become immobile and die. It also partially inhibited invasion and stopped spinach growth when it induced significant amounts of endogenous 20E. Nevertheless, the few J2 that did infiltrate did not show signs of aberrant moulting. There is no evidence that worms biosynthesise ecdysteroids, and efforts to identify 20E and its precursor, ecdysone, in Meloidogyne incognita and Meloidogyne arenaria have been fruitless (Chitwood et al., 1987). The genes involved in moulting in Meloidogyne may be revealed by the complete genome sequences of *Meloidogyne hapla* (Opperman et al., 2008) and *Meloidogyne incognita* (Abad et al., 2008).

Reproduction:

According to Evans' review, nematodes use a variety of asexual and sexual reproduction techniques (1983). Meloidogyne is one of the plant-parasitic nematodes investigated in great detail (Chitwood and Perry, 2009). The process of fusing haploid male (spermatocytes) and female (oocyte) gametes to create a diploid zygote that restores the 2n chromosomal complement is known as sexual reproduction (amphimixis). Sex ratios in species like *A. tritici* and *D. dipsaci* are genetically determined, with females being homogametic (XX) and males being heterogametic (XO or XY). There are no sex chromosomes in genera like Globodera, Heterodera, and Meloidogyne, and sex ratios may be affected by environmental variables. Moreover, females in some species, such as Radopholus, Pratylenchus, and Heterodera, can be impregnated by more than one male, leading to the genetic variety of the progeny.

Plant response to nematode infections:

Scientists and researchers have discovered several naturally occurring genes that contribute to developing plant nematode resistance. Nematode-resistant plants have not been successfully bred using conventional methods. In order to mitigate nematode infestations, RNA interference (RNAi) technology has become a dependable approach (Tamilarasan and Rajam, 2013). There are two primary forms of plant resistance to nematodes: passive and active resistance.

Anatomical, physiological, and pharmacological barriers influencing nematode infestation are passive resistance examples. Conversely, active resistance entails histological alterations that result in the nematode's death by forming necroses around it (Giebel, 1982).

It has been determined that some genes give resistance to particular nematodes. For example, the tomato (*Solanum lycopersicum*) Mi-1.2 gene is resistant against root-knot nematodes, while the HS1pro1 gene is resistant against sugar beet cyst nematodes. According to studies, isogenic plants are resistant to nematode pressures, up to 200,000 eggs per plant. Furthermore, potatoes' potato cyst nematode (*Globodera pallida*) is resistant to the GPa2 gene (Briar et al., 2016; Ralmi et al., 2016). Several metabolites, including tridecane, limonene, 2-isopropyl-3-methoxypyrazine, and methyl salicylate, can affect nematode mobility and prevent them from finding appropriate hosts (Sikder and Vestergard, 2020).

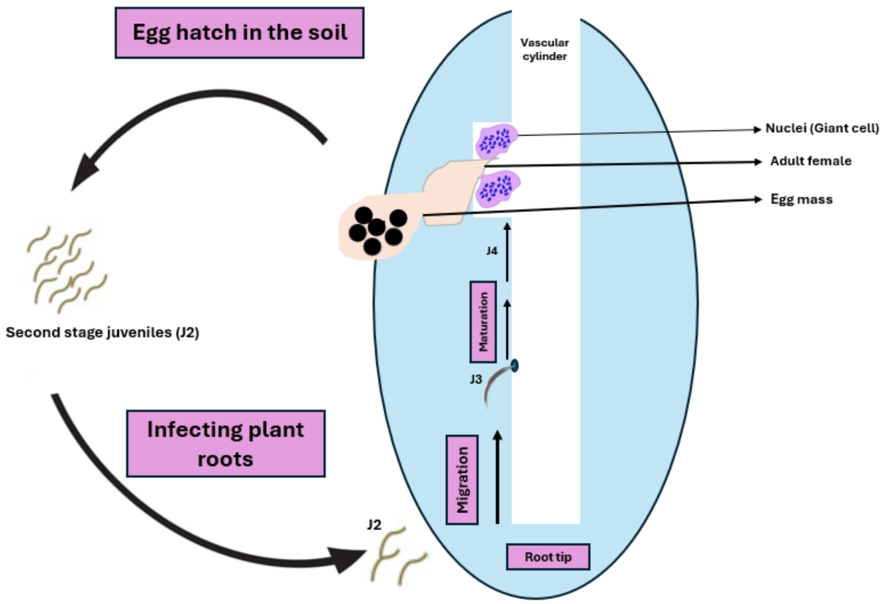

Figure 4. Mechanism of Parasitic root nematode

Impact of plant parasitic nematodes on crops:

With almost 4,100 species known to date, plant-parasitic nematodes represent a substantial financial barrier to agricultural crop production (Decraemer and Hunt, 2006). Crop loss caused by parasitic nematodes is estimated to be between $80 and $118 billion annually. These harmful nematodes, which comprise around 15% of all species found, primarily target the roots of important crops. This disturbance negatively impacts plant development, quality, and yields because it makes it difficult for plants to absorb water and nutrients. Because they parasitize plants, animals, and fungi, nematodes in the Tylenchida order are remarkable and ranked among the most important agricultural pests (Nicol et al., 2011).

Wheat:

With an annual production of about 758 million tons, wheat (*Triticum aestivum*) is the most important cereal crop in the world and is a mainstay for 40% of the world's population (FAO, 2017). Nonetheless, cereal cyst nematodes (*Heterodera spp.*) pose a significant danger to wheat yields, especially those belonging to the *Heterodera avenae* group, which comprises *H. avenae, H. filipjevi, and H. latipons.* These pests harm wheat and other important cereals, including oats (*Avena sativa*) and barley (*Hordeum vulgare*). These nematodes cause an estimated $3.4 million in annual profit loss for wheat-growing regions in the United regions, including Idaho, Oregon, and Washington (Smiley et al., 2010). According to Bonfil et al. (2004), *H. avenae* damage alone may produce yield losses in some areas that range from 30% to a disastrous 100%.

Rice:

Most of the world's population depends on rice (*Oryza sativa L.*), of which 480 million tons are produced worldwide (Childs et al., 2017). Plant-parasitic nematodes are one of the most important soil-borne pests that harm rice, which cause yield losses of 10–25% each year globally. The production of rice is impacted by more than 100 nematode species, with *Meloidogyne spp.* they are being common and incredibly detrimental to rice and other crops cultivated in temperate and tropical climates. *Meloidogyne graminicola* is one of the most damaging of them, with the ability to cut rice harvests by as much as 80% (Soriano et al., 2000). According to Pokharel et al. (2007), signs of infected plants include hook-shaped galls, slowed growth, fewer tillers overall, and poor development and reproduction.

Maize:

Across the globe, maize (*Zea mays*) is widely grown, with North America, Asia, and Europe producing the most (Nicol et al., 2011). Although there are more than 50 species of nematodes that are known to parasitize corn globally, the most harmful ones are the root-knot (*Meloidogyne spp*.), root lesion (*Pratylenchus spp*.), and cyst (*Heterodera spp*.) worms. The US has economic severe concern regarding the lesion nematodes (*Pratylenchus* spp.) and the maize cyst nematode (*Heterodera zeae*). Nematode infections in maize usually show up as mild galling, chlorosis of the leaves, and poor plant development (Norton et al., 1983). Moreover, maize growth stunting associated with the needle nematode *Longidorus breviannulatus* may result in yield losses as high as 60%.

Potato:

As a member of the Solanaceae family, potatoes (*Solanum tuberosum*) are the third most significant crop in the world, with over 376 million tonnes being produced globally in 2013 (FAOSTAT, 2017). Particularly well-known for severely reducing potato crop yields are cyst nematodes. Originating in South America, *Globodera rostochiensis* and *Globodera pallida* also prey on other members of the Solanaceae family, including tomatoes and woody nightshade. These nematodes are thought to cause the United Kingdom to lose £50 million a year in losses and are considered quarantine pests in several nations, including the United States. The stem worm Ditylenchus destructor and the root-knot nematodes (*Meloidogyne spp.*) also pose a significant threat to potatoes. Four species of root-knot nematodes impact potato output in the United States; the most important species is the Columbian root-knot nematode (*Meloidogyne chitwoodii*) (Santo et al., 1981). Furthermore, *D. destructor* is a primary host of the sweet potato (*Ipomoea batatas* L. Lam), with yield losses as high as 100% in certain production zones, including China, the world's largest producer (Zhang et al., 2006).

Sweet potato:

Cultivating sweet potatoes since prehistoric times, *Ipomoea batatas* (L.) Lam, has been an important plant throughout human history. It has been a staple food source for recorded history; its global production is estimated at 105 million metric tons. Sweet potatoes are the sixth most important food crop in the world. However, their cultivation has improved people's economic standing, particularly in underdeveloped countries where they are ranked the fifth most important crop (CIP International Potato Center, 2014). However, plant-parasitic nematodes cause the annual loss of about 10.2% of sweet potato yields (Decraemer et al., 2006). Of particular concern are root-knot nematodes (RKNs), which can cause symptoms like growth retardation, leaf yellowing, irregular flower output, and the creation of galls on roots. This causes the fleshy store roots to break and necrotize and reduce the absorption of nutrients and water. Because storage roots have a high economic value, growers are concerned about root breaking.

Symptoms of nematode infestation:

Nematodes that consume roots produce symptoms above ground that resemble different kinds of root injury. The leaves could wilt and lose their luster. Nematodes can cause long-term root stress, leaf yellowing and loss. Compared to healthy plants, new growth spurts typically have fewer, smaller leaves and are weaker overall. When there is a drought or low water levels, infected plants typically wilt more quickly than uninfected plants. The harm is usually unevenly distributed because nematodes are rarely dispersed equally throughout the soil. Nematode-caused root symptoms might differ widely. A few nematodes, such as root-knot and some foliar varieties, cause the tissues they feed on to develop abnormally. Others may cause patches of dead tissue to remain behind by preventing root growth or killing cells as they pass through the roots. Depending on the nematode species, damage might take the form of galls, stunted growth, or decaying roots. Often, infected roots have a darker appearance than healthy ones. Damage caused by nematodes to roots increases their vulnerability to bacterial and fungal infections, which can result in illnesses such as root rot and wilt. Furthermore, nematodes can spread certain viruses (Barker and Davis, 1996).

Management Strategies for Plant Parasitic Nematodes:

Developing environmentally safe and non-chemical methods has dramatically outpaced using chemical nematodes. These strategies include sanitation, soil management, and helpful biological agents. Biological techniques exhibit considerable promise as substitutes for managing infestations of plant-parasitic nematodes (Collange et al., 2011). Biological Control Agents (BCAs), sometimes known as "biopesticides," are organisms or their byproducts that fight pests. In general, chemicals intended to protect plants that are not chemically created but instead come from natural substances or live organisms as a result of species co-evolution are referred to as biopesticides. It is advised to utilize them to manage bio-aggressors and control pests to protect the environment and biocenosis better. Plant-parasitic nematodes can be eradicated by biological agents, which include bacteria, fungi, actinomycetes, and other microbes. These agents are particular to their host. The most common bacteria and fungi in the soil ecosystem have an immense potential for controlling nematodes (Blyuss et al., 2019; El-Eslamboly et al., 2019). This review investigates the use of actinomycetes, bacteria, and fungi as plant-parasitic nematode control agents.

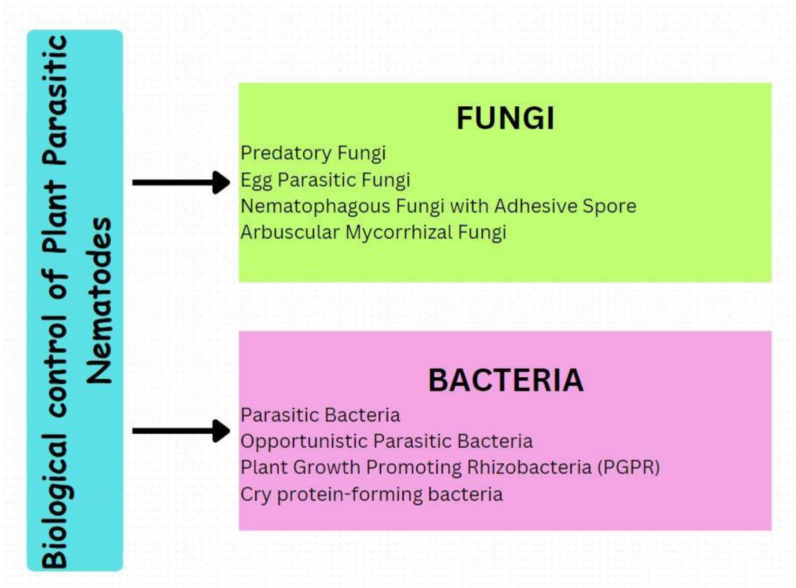

Figure 5. The mechanism of biological control of plant parasitic nematode

Fungi: A Biocontrol Agent Against Root-Knot Nematodes

Plant-parasitic nematodes, such as *Meloidogyne spp*., the root-knot worm, are particularly vulnerable to attack by nematophagous fungi (Brand et al., 2004; Collange et al., 2011). The worm's cuticle is penetrated, organic soil debris is broken down and absorbed, and the nematode is invaded and digested as part of their infection mechanism (Huang et al., 2004). Nematode cuticles and egg walls are important components of fungal invasion. According to Huang et al. (2004), these nematode-feeding fungi predate the invasion of vital cuticle components like collagen, chitin, and fiber. Nematophagous fungi are categorised based on how they inhibit plant-parasitic nematodes (Cayrol et al., 1993).

A. Predatory Fungi

Carnivorous fungi, sometimes predatory fungi, grow on the epidermis and consume other living things by ensnaring and feeding on them (Abd El-Rahman and Mohamed, 2014). These fungi, which belong to Basidiomycota, Ascomycota, and Mucoromycota, have over 200 species identified. Nematophagous fungi are those that eat plant-parasitic nematodes, which include a large number of these fungi. While certain fungus, such as *Arthrobotrys anchonia*, *Arthrobotrys dactyloides*, and *Dactylaria brochopaga*, build constrictive rings to capture nematodes, others, including *Arthrobotrys oligospora* and *Arthrobotrys superba*, use a network trapping method. Despite being saprophytic by nature, these nematophagous fungi can capture nematodes in the soil during their first larval stage or as free adults. Their importance is found in the peptides that are produced when extracellular proteases hydrolyze the cuticles of worms (Huang et al., 2004).

B. Egg-Parasitic Fungi

Nematode eggs can be infected and destroyed by egg-parasitic fungus. Numerous of this fungus can enter dead eggs and are saprophytic. Verticillium, Pochonia, and Paecilomyces species are a few examples. Two of the most potent egg parasites are *Pochonia chlamydosporia* and *Paecilomyces lilacinus*. Particularly *P. lilacinus* has been shown to control root-knot nematodes on tomatoes, eggplants, and other vegetable crops, including *M. incognita* and *M. javanica* (Verdejo-Lucas et al., 2002; Van Damme et al., 2005; Goswami et al., 2006; Haseeb and Kumar, 2006).

C. Adhesive Spore-Forming Nematophagous Fungi

Several classes of fungi use sticky spores to parasitize plant-parasitic nematodes. For example, biflagellate zoospores on the cuticles of nematodes can generate traps for oomycete fungi like *Myzocytium lenticulare*, *Catenaria anguillulae*, and *Myzocytium anomalum*. Zygomycete fungi, such as *Myzocytium anomalum*, produce spherical conidia, which grow germinative filaments following attachment and create new conidiospores. The spores of deuteromycete fungi, including *Meria coniospora*, have a club form and adhere to the host through their anterior portion (Cayrol et al., 1992).

Bacteria: A Biocontrol Agent Against Root-Knot Nematodes

Bacteria are single-celled, microscopic organisms found in water, soil, acidic hot springs, and even radioactive waste (Fredrickson et al., 2008). In addition, they can coexist symbiotically or parasitically with plants and animals in the deep biosphere of the Earth's crust. A notable class of biological agents, microorganisms have been the source of several commercial treatments designed to manage phytonematodes (Hallmann et al., 2009). When managing plant-parasitic nematodes, Bacillus species stand out among the others. One well-known rhizobacterium, Bacillus subtilis, has gained global recognition as a biopesticide against phytopathogenic nematodes (Prakob et al., 2009). To regulate root-knot nematodes, bacteria use a variety of strategies, such as direct parasitism, antibiosis, and nutrient competition (Mendoza et al., 2008; Lee and Kim, 2016; Cawoy et al., 2011). Generating toxins, volatile organic compounds (VOCs), and medications makes antibiosis very effective (Saraf et al., 2014). Furthermore, it is known that other rhizobacteria, including Pasteuria, Pseudomonas, and Streptomyces, can fight against nematodes that cause knotting in roots. Through seed treatment under pot settings, Bharali et al. (2019) discovered that bacterial bioagents were superior to fungal ones in controlling root-knot nematodes in black gram.

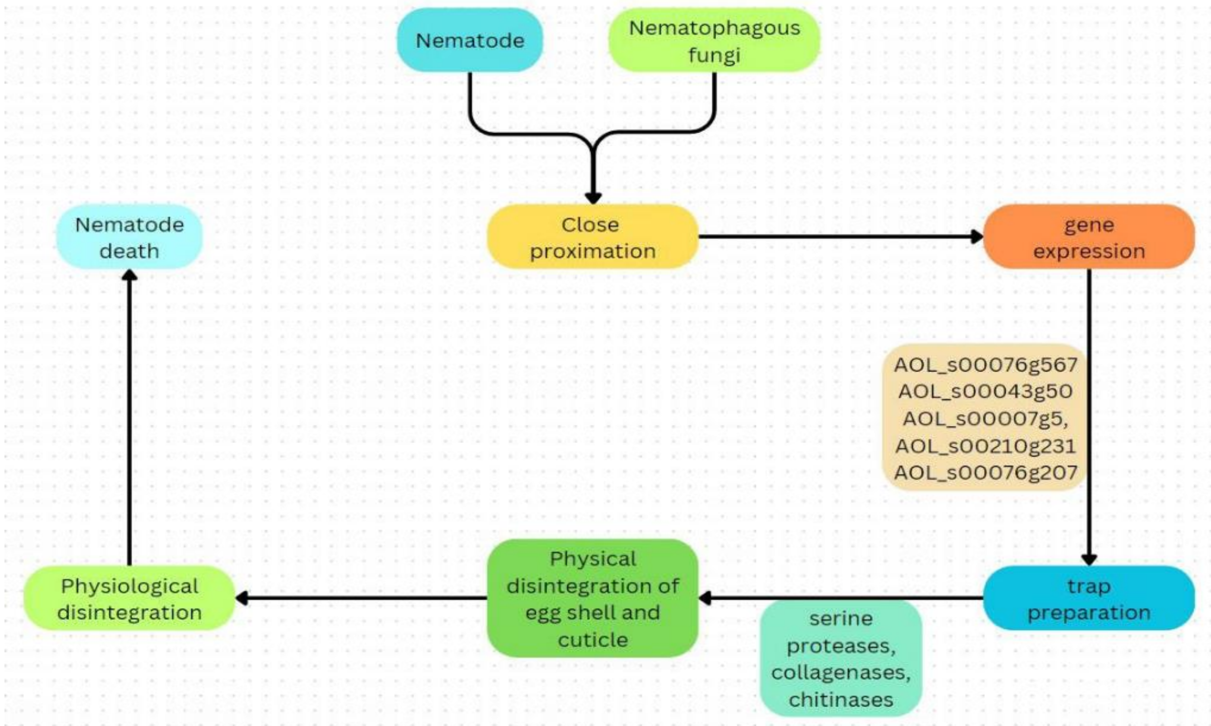

Figure 6. Diagrammatic representation of fungal antagonists of plant parasitic nematodes

Production of Anti-Nematode Compounds of plants:

In response to the invasion of plant-parasitic nematodes (PPNs), plants release secondary metabolites. For instance, the presence of the phenolic compound chlorogenic acid in a variety of plants, such as those in the Solanaceae family (Hung and Rohde, 1973; Pegard et al., 2005), rice (Plowright et al., 1999), and carrots (Knypl et al., 1976), suggests that these plants share a defence mechanism against PPN infections. Although there is a strong correlation between PPN resistance levels and chlorogenic acid production, the compound itself only exhibits mild nematode activity against Meloidogyne incognita (D'Addabbo et al., 2013) and moderate activity against the false root-knot nematode Nacobbus aberrans (López-Martínez et al., 2011). The reason for this poor connection could be that plants are particularly poisonous or unstable when it comes to the metabolized metabolites of chlorogenic acid, which may have increased nematicidal activity. Orthoquinone, which is poisonous to PPNs, can be produced through chlorogenic acid hydrolysis to quinic and caffeic acid (Sato et al., 2019). However, more research is required to determine the precise functions of orthoquinone and caffeic acid in PPN resistance.

Phenylphenalenone anigorufone is another phenolic molecule that builds up at the sites of infection of the burrowing worm *Radopholus similis* in a resistant cultivar of banana (*Musa* sp.) (Dhakshinamoorthy et al., 2014). The development of massive lipid-anigorufone complexes within the bodies of *R. similis* renders anigorufone highly nematicidal. Additionally, this substance is an antifungal phytoalexin triggered by infection with the harmful fungus *Fusarium oxysporum* (Luis et al., 1997). Notably, anigorufone inhibits succinate dehydrogenase in the mitochondrial respiratory complex II, which results in the death of the human protozoan parasite Leishmania (Luque-Ortega et al., 2004). However, the precise harmful mechanism of anigorufone in PPNs and its connection to the creation of lipid-anigorufone complexes are still unknown.

As nematicides, nemastatic substances (which impede movement but do not kill), repellents, egg hatching inhibitors, flavonoids, a broad class of secondary metabolites, are essential for PPN resistance (Chin et al., 2018). Flavonols (kaempferol, quercetin, myricetin), isoflavonoids, and pterocarpans (medicarpin, glyceollin) are notable anti-nematodal flavonoids. While myricetin, quercetin, and kaempferol operate as hemostatic agents and repellents to juvenile *M. incognita*, kaempferol suppresses the hatching of *R. similis* eggs (Wuyts et al., 2006). Furthermore, medicarpin suppresses *Pratylenchus penetrans* motility in a concentration-dependent way (Baldridge et al., 1998). Patuletin and patulitrin also show anti-nematodal properties. According to Faizi et al. (2011), quercetin and rutin have nematicidal effects on the infectious juveniles of *Heterodera zeae*.

Plants that are resistant to infection frequently release specific flavonoids. Glyceollins, for instance, are soybean-specific prenylated pterocarpan phytoalexins that react to infection and are produced by soybean varieties resistant to *Meloidogyne incognita* (Davis et al., 1989). Notably, it has been demonstrated that glyceollin inhibits *M. incognita's* mobility. Resistant soybean cultivars accumulate higher concentrations of glyceollin than by susceptible ones. In resistant roots, glyceollin I, one particular isomer, tends to concentrate in tissues close to the nematode's head (Huang and Barker, 1991). This implies that the buildup of glyceollin is directed towards the site of infection.

Apart from phenolic chemicals, marigold and asparagus are other plants that have been found to have nematode-antagonistic qualities. The nematicidal activity of marigold roots is demonstrated by their ability to successfully penetrate the nematode's hypodermis and release α-terthienyl, a chemical that causes oxidative stress (Faizi et al., 2011). Similarly, asparagus yields asparagusic acid, which can prevent *Globodera rostochiensis* and *Heterodera glycines* from hatching (Chitwood, 1992).

The Brassicaceae family of plants is known for its broad-spectrum antibacterial activities against plant-parasitic nematodes (PPNs). Examples of these plants are those that yield isothiocyanates and indole glucosinolates. As well as being poisonous to both RKNs and the semi-endoparasitic nematode *Tylenchulus semipenetrans*, isothiocyanates are known to impede the hatching of both cyst nematodes (CNs) and root-knot nematodes (RKNs) (Zasada and Ferris, 2004). The cytochrome P450 enzymes CYP79B2, CYP79B3, and PAD3 control the formation of camalexin, an indole alkaloid glucosinolate phytoalexin, in Arabidopsis (Mikkelsen et al., 2000). While camalexin-deficient pad3 mutants are more susceptible to RKNs than wild types, Arabidopsis mutants lacking in these enzymes, such as cyp79b2/b3, exhibit higher vulnerability to CNs (Shah et al., 2017). Although there is no evidence of direct toxicity, some indole glucosinolates, such as camalexin, appear to affect PPNs.

In addition to nemastatic substances and nematicides, plants may defend themselves by interfering with PPN chemotaxis. Nematode attraction to roots can be decreased by ethylene, a hormone released in response to wounding and pathogen invasion (Booker and DeLong, 2015). PPNs seem less drawn to Arabidopsis mutants that overproduce ethylene, but more drawn to those treated with ethylene-synthesis inhibitors or ethylene-insensitive mutants (Fudali et al., 2013).

Conclusion:

Around the world, parasitic nematodes seriously threaten agricultural production, affecting crop yields and quality. The harm they cause, which is frequently overlooked, highlights the need for thorough and integrated pest control methods. The several strategies plants use to ward off these nematodes such as chemical deterrents and physical barriers have been covered in this chapter. Ensuring food security requires effective control of parasitic nematodes, particularly considering the world's expanding population and rising food demands. We could mitigate the negative consequences of these pests by studying the intricate relationships that nematodes have with their host plants and using this information to create effective management measures.

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Chapter- 7

Marine Collagen: A Viable and Eco-Friendly Alternative in Pharmaceuticals

Maitrayee Banerjee Mukherjee

Keywords: Bone, Cartilage, Immunomodulatory, Marine collagen, Wound

Abstract:
Marine collagen, obtained from the by-products of aquatic invertebrates plays a significant role in several biomedical fields. It is essential for creating biomaterials used in tissue scaffolds, absorbable sutures and wound treatment matrices and for its applications in cosmetics and drug delivery systems. Marine species provide an ideal collagen source due to their lack of religious limitations and the absence of reported transmissible diseases. Studies indicate that collagen derived from fish possesses bioactive properties including regenerative, antioxidant, antibacterial, anti-inflammatory, and immunomodulatory effects along with the ability to inhibit angiotensin-converting enzyme activity. This review explores the scientific advancements surrounding collagen derived from marine organisms and fish by-products.

Introduction:

Collagen is a complex fibrous protein and the primary structural component of the extracellular matrix, present in various connective tissues like skin, bones, ligaments, tendons, cartilage, and interstitial tissues in parenchymal organs. It consists of amino acids like glycine, proline, and hydroxyproline, which comprise 33% and 15-30% of its composition, respectively and prevent the formation of alpha-helix or beta-sheet structures. The basic building block of collagen, tropocollagen, comprises right-handed triple helices made from alpha chains, largely following a repeating Gly-X-Y amino acid sequence. X typically represents proline (Pro), while Y is often hydroxyproline (Hyp), though other amino acids, such as alanine, serine, threonine, lysine, and others, can also be found.

Currently, 29 distinct collagen types have been classified and organized into families such as fibrillar collagens, fibril-associated collagens with interrupted triple helices (FACITs), membrane-associated collagens (MACITs), and others with multiple triple-helix domains (MULTIPLEXINs). Microfibrils are composed of aligned tropocollagen molecules measuring around 300 nm in length and 1.5 nm in diameter, with a molecular weight of 285 kD. These molecules aggregate to form microfibrils, varying between 10 and 125 in number, arranged into fibrils ranging from 10 to 200 nm in diameter. The fibrillar types, such as I, II and III, comprise the majority of vertebrate collagen, contributing to tissue's structural integrity and tensile strength, and are responsible for the skin's elasticity (Lim et al., 2019). The fibrillar

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arrangement of collagens results in a distinctive cross-banded pattern in electron microscopy due to the staggered structure of the helices (Bella and Hulmes, 2017).

FACIT collagens do not independently form fibrils but associate with existing collagen fibrils. Their interrupted helices contain non-collagenous regions that enable joint formation and proteolytic cleavage, which helps overcome the protease resistance of the native helices. MULTIPLEXINs, such as types XV and XVIII, feature hybrid proteoglycan-collagen structures. For example, type XV contains chondroitin sulphate chains, while type XVIII is a heparan sulphate proteoglycan (HSPG), contributing significantly to its molecular weight (Halfter et al., 1998). MACITs, with interrupted helices, are involved in cell adhesion and signalling. Several other less abundant collagen types perform specialized roles in specific organs.

Collagen's versatility extends to its applications in biomedical devices, dermal grafts, implants, food products, beverages, and cosmetics, thanks to its ability to absorb water, flexibility, and potential to form 3D structures. Additionally, its surface properties—such as stability, cohesion, and film formation—make collagen ideal for tissue engineering, drug delivery and regenerative medicine (Lim et al., 2019).

Historically, collagen used for tissue engineering had been sourced from terrestrial animals, mainly pigs and cows. However, due to concerns about diseases like bovine spongiform encephalopathy (BSE) and religious restrictions in certain cultures, marine sources of collagen have become an increasingly desirable and cost-effective alternative (Easterbrook et al., 2008).

In recent years, the extraction and utilization of collagen from marine sources have aligned with the principles of the circular economy (Saha, 2023). Industries can reduce waste by repurposing fishery by-products such as skin, scales, and bones while generating valuable materials for biomedical and cosmetic applications (Mukherjee et al., 2022; Sanyal et al., 2023). This approach promotes resource efficiency and sustainability, contributing to a closed-loop system where waste is minimized and resources are continually reused.

Characteristics of Marine Collagen

Marine environments, covering over 70% of the Earth's surface, contain a vast range of species, representing around half of global biodiversity. This diversity provides a valuable source of collagen and other natural substances for industries such as cosmetics, nutraceuticals, medical devices, and biocompatible materials. Marine collagen can be obtained from various organisms, including sponges, jellyfish, octopuses, sea urchins, squid, starfish and algae. Marine collagen holds several advantages over mammalian collagen, such as enhanced solubility in water, biocompatibility, biodegradability, lower immunogenicity, easier extraction methods, and lower production costs (Lim et al., 2019; Ali, 2024).

Structurally, marine collagen is similar to mammalian collagen with glycine as the predominant amino acid, accounting for over 30% of its composition. Although marine collagen generally has lower concentrations of amino acids like proline and hydroxyproline, cold-water fish species often exhibit higher levels of amino acids such as serine and threonine. The hydroxyproline content influences collagen's rigidity and denaturation temperature, contributing to the overall stability of its triple helix. Freshwater fish such as tilapia, have shown amino acid profiles and thermal stability similar to mammalian collagen. Hydroxyproline and hydroxylysine help maintain collagen's structural integrity and heat resistance, thus influencing its thermal equilibrium (Oslan et al., 2022).

Extraction and Purification of Marine Collagen

Collagen extraction typically employs three key methods **:** neutral salt solubilization, acid solubilization and pepsin solubilization (Li et al., 2020). The neutral salt method involves extracting loosely cross-linked collagen molecules using salt solutions, followed by purification processes such as dialysis, sedimentation, and centrifugation. In contrast, dilute acidic solvents like citrate buffer, acetic acid, or hydrochloric acid (pH 2-3) are generally more effective for collagen extraction. However, collagen from sources like bones, cartilage, or older organisms, which have higher levels of keto-imine cross-links, displays lower solubility in mildly acidic solutions (Blanco et al., 2017).

Hydrolysed collagen exhibits a range of beneficial biological activities, making it valuable for nutritional, medical, and food industries. It has been reported to assist in treating conditions such as brittle bone disease, diabetes, gastric ulcers, hypertension and skin hydration and it functions as a preservative (Barzkar et al., 2019). Given its extensive industrial applications, collagen is increasingly utilized in pharmaceuticals, food products, beverages, cosmetics, tissue engineering and healthcare. Its outstanding properties—haemostatic activity, biodegradability, and low antigenicity—are the main reasons for its use in therapeutic and pharmacological fields (Lim et al., 2019).

Collagen hydrogels form through polymerization of collagen suspensions, typically at room temperature for about 15 minutes, then transition to a non-transparent state. Once incubated at 37°C for 45-60 minutes, a medium is added, and the gels are detached gently, often with a pipette, to ensure they float within the medium (Govindharaj et al., 2019). These hydrogels create intricate 3D networks capable of absorbing large volumes of water, enhancing their biocompatibility, flexibility, and suitability for biotherapeutic applications. Collagen hydrogels are particularly useful in tissue and cell cultures, tissue regeneration, biofabrication, drug delivery and soft gelatine gel development (Wang et al., 2015).

Marine-derived polymers have gained significant attention recently as natural, eco-friendly alternatives for developing biocompatible materials (Barzkar et al., 2019; Sankarapandian et al., 2023). Collagen biopolymers extracted from aquaculture products such as fish skin or jellyfish offer increased value and functionality for biomaterials while aligning with circular economy strategies. Marine collagen also reduces infection risks and enhances immune response (Govindharaj et al., 2019).

Marine Collagen in Bone and Cartilage Regeneration

Alves et al. explored the immune response to collagen and gelatine derived from blue sharks and codfish by characterizing these materials and evaluating endotoxin levels. After exposing bone marrow-derived macrophages to the collagen, they measured gene expression and protein levels of pro-inflammatory and anti-inflammatory cytokines. The results showed that shark collagen produced the lowest immune response as indicated by reduced levels of pro-inflammatory cytokines, inducible nitric oxide synthase (Nos2), and increased Arginase 1 (Arg1). Although shark gelatin induced higher pro-inflammatory responses, it also boosted IL-10 (an anti-inflammatory cytokine) and Arginase, markers of M2-like macrophages.

In mouse models, both materials resulted in temporary neutrophil recruitment, mostly subsiding within 24 hours. When mouse osteoblast cells (MC3T3-E1) were treated with fish collagen peptides (FCP), they showed increased gene expression of collagen-modifying enzymes such as lysyl hydroxylase (LH) 1-3, particularly LH2 and lysyl oxidase-like proteins (LOXL) 2-4. This was accompanied by enhanced collagen deposition and matrix mineralization, as *in vitro* mineralization assays demonstrated. FCP also increased lysine hydroxylation, boosted hydroxylysine-aldehyde cross-link formation, and accelerated cross-link maturation compared to controls, indicating the potential of FCP in bone regeneration (Yamada et al., 2013).

Further research supports marine collagen's positive impact on bone marrow stem cells in rats. Liu et al. reported that a fish collagen concentration of 0.2 mg/mL promoted cell survival and increased the expression of osteogenic markers (RUNX2, ALP, OPN, and OCN) and endothelial markers (CD31, VE-cadherin, and VEGFR2) (Liu and Sun, 2014). Another study revealed that hydrolyzed fish collagen enhanced human periodontal ligament cell viability and osteogenic differentiation, as shown by increased expression of osteogenic markers and proteins like alkaline phosphatase and osteocalcin (Liu and Sun, 2015). Interestingly, hydrolysed fish collagen also stimulated rat bone marrow mesenchymal stromal cells to produce anti-inflammatory markers (IL-6, TGF-β1, and PGE2), demonstrating that the immunomodulatory properties of collagen remain intact even in osteogenically differentiated cells (Liu and Sun, 2019). Additionally, marine collagen-derived bioactive peptides have been shown to enhance calcium and zinc absorption, acting as antiosteoporosis agents. Marine collagen hydrolysates reduce pro-inflammatory markers associated with osteoarthritis while promoting collagen synthesis in articular chondrocytes (Bourdon et al., 2021).

Marine Collagen in 3D Culture

Three-dimensional (3D) cell cultures provide a more realistic environment for cellular growth, allowing cells to interact with the extracellular matrix (ECM) in all directions. This contrasts conventional two-dimensional (2D) cultures, where cells are confined to a flat surface. 3D cultures, which can be created with or without scaffolds, offer a more accurate representation of biological environments, simulating in vivo conditions. Due to its biocompatibility and capacity to support cell adhesion, proliferation, and tissue formation, Marine collagen holds considerable potential for 3D cell culture applications (Urzi et al., 2023). Its similarity to the ECM makes it an ideal candidate for developing physiologically relevant environments for various cellular processes.

Marine collagen has found increasing applications in tissue engineering, regenerative medicine, and pharmaceutical testing. However, challenges such as high production costs and material variability persist, requiring further research. Marine-derived polymers like alginates, carrageenans, fucoidans, and chitosans, sourced from organisms such as algae, crustaceans, and fish, are being incorporated into bio-inks for bioprinting. These marine-derived biomaterials are becoming promising scaffolds for 3D cell and tissue cultures (Zhang et al., 2019). The use of 3D systems to evaluate marine-derived materials is expanding, offering benefits over traditional 2D models.

Marine Collagen for Skin Regeneration and Wound Healing

Marine collagen peptides (MCPs), derived from aquatic invertebrates through biochemical and enzymatic hydrolysis, are characterized by their lower molecular weight, enhancing water solubility and making them easier to absorb in biological systems. Wang et al. showed that MCPs extracted from salmon skin improved dermal wound tensile strength in rats, largely due to an increase in hydroxyproline levels. Additionally, collagen from marine tilapia skin and bovine collagen nanofibers accelerated wound healing in collagen-treated rats compared to controls (Chen et al., 2019).

A randomized triple-blind clinical trial on women aged 45-60 assessed the effects of freshwater fish-derived collagen on skin wrinkles, elasticity, and flexibility. After three months of supplementation, a 35% reduction in wrinkles was observed (Wang et al., 2015). Six weeks post-treatment, participants exhibited significant improvements in skin elasticity, particularly on the cheeks (Evans et al., 2021). Marine collagen, known for its potent free radical scavenging capabilities, neutralizes reactive and unstable free radicals that can damage cellular membranes, degrade dermal macromolecules, and harm DNA, all factors linked to skin aging (Geahchan et al., 2022).

Conclusion

Collagen, a crucial protein that makes up approximately 30% of the body's total protein, is found primarily in skeletal tissues, cartilage, the gastrointestinal tract, teeth, dermis, and adventitia. Due to its favourable properties, such as low immunogenicity, marine collagen has become widely used in biopharmaceuticals and cosmetics. Marine species are rich in biologically active compounds that show promise for applications in medicine, tissue engineering, and cosmetics. Notable sources of marine collagen include fish (dermis, skeleton, scales, and cartilage), molluscs, and marine invertebrates like jellyfish, sea cucumbers, sea urchins, polyps and squid.

Research indicates that marine collagen promotes the migration of keratinocytes and fibromuscular tissue, stimulating angiogenesis within the skin. It has also been effective in preventing and treating age-related metabolic bone diseases such as osteoarthritis and osteoporosis, by increasing bone mass and tensile strength. Due to its dynamic pharmacological applications, marine collagen has emerged as a superior alternative to terrestrial collagen sources. As demand for natural products rises, collagen is now used in emulsifiers, foaming agents, stabilizers, hydrogels, microencapsulation and more. Advances in analytical techniques have allowed for more detailed exploration of marine collagen's properties, making it a promising candidate for various biomedical and industrial uses.

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Chapter- 8

A Brief Review on Solar Photovoltaic: A Key to Sustainable Development

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Keywords: Depletion layer, Photovoltaic, Semiconductor, Sustainable development

Abstract:
Taking urgent steps towards embracing green or renewable energy sources is essential to address the increasing energy demands and tackle the ongoing climate crisis. To advance society's sustainable development, switching to solar energy is crucial due to its abundant availability and reliable, nearly limitless source, making it the most attractive option for an eco-friendly power source. Solar cells or photovoltaic devices are durable and reliable and can convert sunlight directly into electricity efficiently without producing noise or pollution. The popularity of solar panels depends on their cost, availability of raw materials, and efficiency. Currently, studies are underway to discover novel materials for solar photovoltaic devices. The objective is to find a system with high efficiency, lower cost, and improved durability. Current data ensure the worldwide progression of the use of solar cells and the increasing rate of efficiency improvement due to extended research.

Introduction:

Energy enhances convenience and comfort in our daily lives. Because of the increasing population and industrialization, the global energy demand is rising constantly. The majority of requests are satisfied through the use of non-renewable energy sources such as fossil fuel and nuclear energy. Overuse of fossil fuels leads to the release of greenhouse gases, resulting in climate change. To safeguard our environment and reduce pollution caused by greenhouse gas emissions, the Kyoto Protocol agreement (Tucker, 1999; Kalogirou, 2009) was implemented. Fossil fuels have a dual impact, affecting both the environment and the finite nature of their sources. The quest for alternative energy sources has been ongoing to address the increasing global energy demands (Tucker, 1999; Nandwani, 1996). Renewable energy sources such as geothermal, solar, wind, tidal, biomass, and hydropower are widely recognized. Clean energy, also called non-carbon-emitting forms of energy, is crucial for environmental sustainability, aligning with SDG 7: Affordable and Clean Energy, which aims to ensure access to affordable, reliable, sustainable and modern energy for all.

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Solar energy is the most appealing option because of its abundant availability and reliable, nearly infinite source (Muhammad et al., 2019; Yadav et al., 2023; Gajbhiye et al., 2024; Singh et al., 2024). This technology contributes significantly to SDG 13: Climate Action by reducing greenhouse gas emissions and supporting global efforts to combat climate change (Mukherjee et al., 2022; Chatterjee et al., 2023).

Humans have been utilizing solar energy for a long time, dating back to the 7th century B.C., when they used sunlight to start fires by reflecting the sun's rays onto reflective surfaces. In the 3rd century B.C., the Greeks and Romans utilized solar power by using mirrors to illuminate torches during religious rituals. In 1839, French scientist Edmond Becquerel observed that a cell with metallic electrodes generated increased electricity in the presence of light, leading to the first recognition of the photovoltaic effect and the creation of the PV cell. In 1954, Daryl Chapin, Calvin Fuller, and Gerald Pearson invented PV technology at Bell Labs. He created the first solar cell capable of absorbing and converting sufficient solar energy to power standard electrical devices. Thanks to technological advancements, we can now use solar energy to fuel satellites and spacecraft that orbit the Earth. These innovations support SDG 9: Industry, Innovation, and Infrastructure, which promotes inclusive and sustainable industrialization and fosters innovation.

By encouraging the use of solar photovoltaics as a critical source of renewable energy, we also contribute to SDG 12: Responsible Consumption and Production, which aims to ensure sustainable consumption and production patterns by reducing reliance on finite resources like fossil fuels and adopting cleaner, renewable alternatives.

Photovoltaic cell and Photovoltaic effect:

A solar cell, also called a photovoltaic cell, is an electronic device that seizes light energy (specifically solar energy) and converts it into electrical energy using the photovoltaic effect. This is essentially a semiconductor-based p-n junction diode. A semiconductor's electrical conductivity lies between a conductor and an insulator. Doping techniques involving intentionally injecting impurities into pure semiconductors can help enhance their conductivity. We obtain either a P-type or N-type semiconductor based on the type of doping element used (trivalent or pentavalent). Excess of negatively charged electrons serves as the majority charge carrier in N-type semiconductors. In contrast, an excess of positively charged holes, which are the absence of electrons, characterize P-type semiconductors. When these two types of semiconductors are combined (using the proper fabrication process), holes from the p-side and electrons from the n-side diffuse through the junction, creating a layer of negative and positive charges on the p-side and n-side, respectively, and forming a depletion layer as depicted in Figure 1. Because of the stationary charge in vicinity of the P-N junction, an electric field is created (from the N region to the P region) that prevents the continued movement of holes and electrons in average condition.

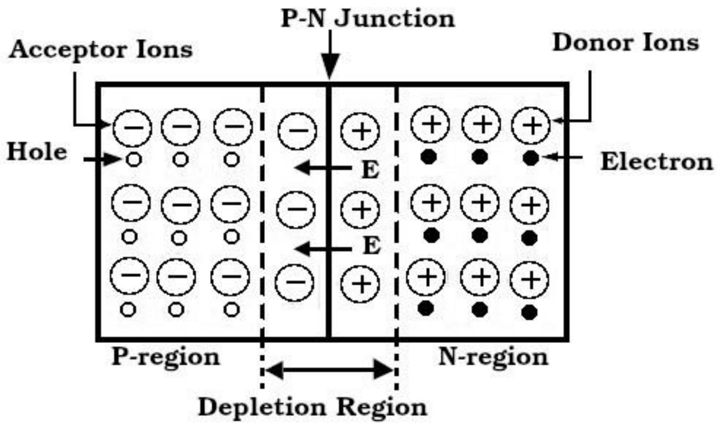

Figure 1. Schematic diagram of P-N junction diode with depletion region.

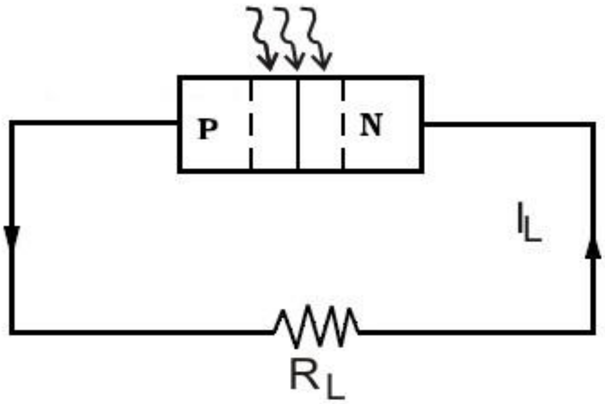

Figure 2. Schematic diagram of PV cell.

Now, suppose light with proper wavelength (for solar cells, sunlight) falls on the PN junction. In that case, the electron-hole pair is generated (Figure 2). If these mobile charge carriers reach the vicinity of the junction before they recombine, the electric field in the depletion region will push the hole in the P side and the electron in the N side. An accumulation of electrons and holes into N and P regions, respectively, generates an electromotive force. This accumulation continues till the electric field due to this accumulation is equal to the previous field generated due to diffusion.

Now, when the endpoints are connected through the load resistance (R_L), the current (I_L)will flow as long as light falls on the P-N junction, and this will act as a photovoltaic cell (PV) cell. The phenomenon is called the photovoltaic effect. When R_L=0, maximum current flows through the circuit, termed a short circuit current (I_{SC}). The open circuit voltage V_{OC} occurs if the circuit has the highest load. The typical open circuit voltage of a PV cell is approx 0.58 volts. Conversion efficiency, the most commonly used metric to assess photovoltaic technologies, is the ratio of electrical energy output to solar energy input. Efficiency results from various system components like short-circuit current, open-circuit voltage and fill factor, all of which are influenced by material properties and production flaws (Węgierek and Billewicz, 2011). The efficiency of a solar panel is calculated by dividing the power output by the total solar energy input.

The solar cell converts power at an efficiency of approximately 27%. Chapin et al. (1954) reported the first solar cell with 6% efficiency in 1954. The well-known Shockley-Queisser (SQ) limit establishes a maximum efficiency for commercially available technologies by considering the equilibrium between photogeneration and radiative recombination (Węgierek and Billewicz, 2013).

Practical structure of solar panel:

Most of the photovoltaic modules currently being used contain silicon solar cells. Silicon ranks as the Earth's second most abundant material, after oxygen. Silicon solar cells offer a lengthy lifespan, high efficiency, and affordable price. Module longevity is anticipated to be at least 25 years. It continues to produce more than 80% of its original power beyond this point. When exposed to sunlight, a typical solar cell generates a voltage of approximately 0.6V. Most applications require greater voltage than this. Solar cells are commonly linked in a series to create a photovoltaic module for proper voltage (Figure 3A), and these modules are then connected in parallel to achieve a higher current.

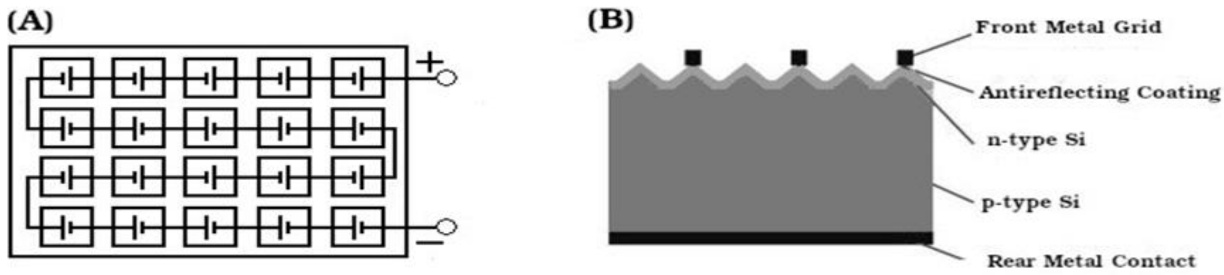

Figure 3. Schematic diagram of (A) a photovoltaic module and (B) a cross-section of a traditional silicon solar cell.

A silicon wafer of the p-type, measuring a few hundred micrometers in thickness and roughly 100 centimeters in size, is used to create a conventional silicon solar cell. The wafer, which forms the "base" of the cell, is weakly doped (about 1016 cm^{-3}). Silicon could be used as either a single- or multi-crystalline structure. Dopant diffusion forms an n-type layer on the wafer's surface, producing the required p-n junction. The n-type layer, also called the "emitter," is significantly thinner than the p-type base and more strongly about 1019 cm^{-3}). Figure 3B depicts a schematic cross-section of a silicon solar cell. The silicon wafer is usually texturized by chemical etching to reduce light reflection from its surface before the n-type emitter layer forms. To further improve light absorption, an antireflection coating can be applied to the surface after the n-type layer forms, made of sin_x or TiO_2, which can reduce reflections and act as passivation to keep charges from becoming trapped at the surface. To provide a back surface field that reduces surface recombination, the rear surface is more highly doped. After that, metal contacts are placed using a printing method, including screen-printing silver or aluminum. While the metal contact on the back of the cell can be continuous, as seen in Figure 3B, a grid-like metal pattern is printed on the front to restrict the quantity of light blocked.

Silicon solar cells can easily be damaged and corroded, so encapsulation steps are incorporated into manufacturing modules to offer adequate protection. The cells connected in series can be enclosed in a transparent polymer, like ethylene vinyl acetate (EVA), and then installed on a piece of glass, which serves as the top, see-through layer of the module. A further barricade against water and gases can be provided by adding another polymer layer, like polyvinyl fluoride, to the underside of the module.

Advancement of Photovoltaic cell:

Solar panels' popularity is influenced by cost, availability of raw materials, and efficiency. Various technologies are utilized in the production of photovoltaic cells, involving material adjustments to vary the photoelectric conversion efficiencies within the cell parts. Ideal material for solar cells will possess a band gap ranging from 1.1 to 1.7 eV and should have a direct band structure. Along these lines, it should also have high photovoltaic conversion efficiency and be readily available and safe for use (Hayat et al., 2019). Because of the development of several unconventional manufacturing techniques for fabricating operational solar cells, photovoltaic technologies can be categorized into four distinct generations (Luque and Hegedus, 2011; Almosni et al., 2018).

First generation: The initial photovoltaic cell technologies rely on mono crystalline (m-si) and polycrystalline silicon (p-si) as well as gallium arsenide (GaAs). Monocrystalline material is commonly utilized for its superior efficiency compared to multi-crystalline material. The estimated theoretical efficiency threshold for first-generation PV cells was around 29.4%, and a value close to this was achieved almost 20 years ago. The efficiency of crystalline silicon photovoltaic cells has increased by 20.1% since they were first developed, rising from 6% to a current record efficiency of 26.1% (Saga, 2010). Table 1 displays the contrast between initial photovoltaic cells (Sharma and Goyal, 2020).

Table 1. Comparison between first-generation photovoltaic cells (Sharma and Goyal, 2020).

Solar cells Based on	Band Gap (eV)	Efficiency (%)	Life span (years)	Advantages	Drawbacks
Monocrystalline silicon (m-si)	-1.1	15 - 24	25	High stability, high performance, long service life	High production cost, issues with absorption, increased sensitivity to temperature, loss of materials
Polycrystalline silicon (psi)	-1.7	10 - 18	14	Cost-effective, simple manufacturing procedure, reduced silicon wastage, more excellent absorption than m-si.	Lower efficiency, higher temperature sensitivity.

Gallium arsenide (GaAs)	-1.43	28 - 30	18	High stability, reduced sensitivity to temperature, and improved absorption compared to m-si	Extremely expensive

Second Generation: This category comprises the microcrystalline and amorphous silicon, copper indium gallium selenide (CIGS), and cadmium telluride/cadmium sulphide (CdTe/CdS). One important enhancement area required was decreasing the significant reliance on semiconductor materials. Regarding efficiency, CIGS holds a record value of 23.4%, which is on par with the top silicon cell efficiencies. They provide enhanced mechanical characteristics suitable for flexible uses, though this may result in decreased effectiveness. Table 2 compares second-generation photovoltaic cells relative to second-generation (Sharma and Goyal, 2020).

Table 2. Comparison between second-generation photovoltaic cells (Sharma and Goyal, 2020).

Solar cells Based on	Band Gap (eV)	Efficiency (%)	Life span (years)	Advantages	Drawbacks
Amorphous silicon (a-si)	-1.7	5 - 12	15	Cost-effective, non-toxic, abundant, high absorption coefficient.	Lower efficiency, challenges in choosing dopant materials, limited minority carrier lifetime.
Copper Indium Gallium Selenide (CIGS)	-1.7	20-23	12	Production requires a smaller amount of material.	Extremely expensive, prone to temperature variations, unstable, extremely unreliable
Cadmium telluride /cadmium sulphide (CdTe / CdS)	-1.45	15 - 16	18	High absorption rate, less material needed for manufacturing.	Lower efficiency, extreme toxicity of Cd, limited Te availability, higher temperature sensitivity.

Third generation: The third iteration of solar cells, which includes tandem, perovskite, dye-sensitized, organic, and new concepts, encompass a variety of strategies, from cost-effective but low-efficiency options (like dye-sensitized and organic solar cells) to pricey but high-efficiency choices (such as III-V multijunction cells) for uses spanning from buildings to space. The third-generation solar cells employ quantum dots, dye-sensitized solar cells, and organic polymers. Quantum dots are available in different sizes and can be customized in terms of their bandgap, which allows them to absorb light that is usually challenging to capture and to be combined with other semiconductors. Current silicon photovoltaic cell technology advancements focus on creating extra energy levels within the semiconductor's band structure. Current research efforts are focusing on enhancing the manufacturing technology and efficiency of third-generation solar cells. The most advanced and promising technology in photovoltaics is third-generation solar cells. Investigations on these are still ongoing. Table 3 displays the comparative analysis of third-generation solar cells (Sharma and Goyal, 2020; Peumans et al., 2003; Gao et al., 2020).

Table 3. Comparison between third-generation photovoltaic cells (Sharma and Goyal, 2020; Peumans et al., 2003; Gao et al., 2020).

Solar cells Based on	Efficiency (%)	Advantages	Drawbacks
dye-sensitized photovoltaic cells	5 - 20	Low production cost, lower operating temperature, efficiency in low light and wide-angle settings, robustness, and longer lifespan.	Issues regarding temperature control, and the presence of harmful and unstable substances.
Organic and polymeric photovoltaic cells	9 -11	Cost-effective processing, reduced weight, thermal stability, and flexibility,	Low efficiency.
Quantum dots	11 - 17	Low energy consumption and low production cost.	High levels of toxicity in nature, degradation
Perovskite	21	Low production cost and simplified structure, high efficiency, lightweight, and flexibility.	Unstable
Multi-junction solar cells	≥36	High performance	Complex, expensive

Fourth generation: Fourth-generation graphene-based solar cells have overcome the limitations of older generations thanks to technological advancements. The fourth-generation cell technologies are currently in the development stage. Fourth-gen photovoltaic cells, termed hybrid inorganic cells, blend the cost-effectiveness and adaptability of polymer thin films with the durability of organic nanostructures like metal nanoparticles, metal oxides, carbon nanotubes, graphene, and their derivatives. These tools, also known as "nano photovoltaics," maybe the bright future of photovoltaics (Wu et al., 2020). The fourth generation comprises inexpensive thin film, metal oxides, metal nanoparticles, graphene, carbon nanotubes, and graphene derivatives. Graphene provides numerous advantages for PV technology, including flexibility, stability, low resistivity, and photo-catalytic properties.

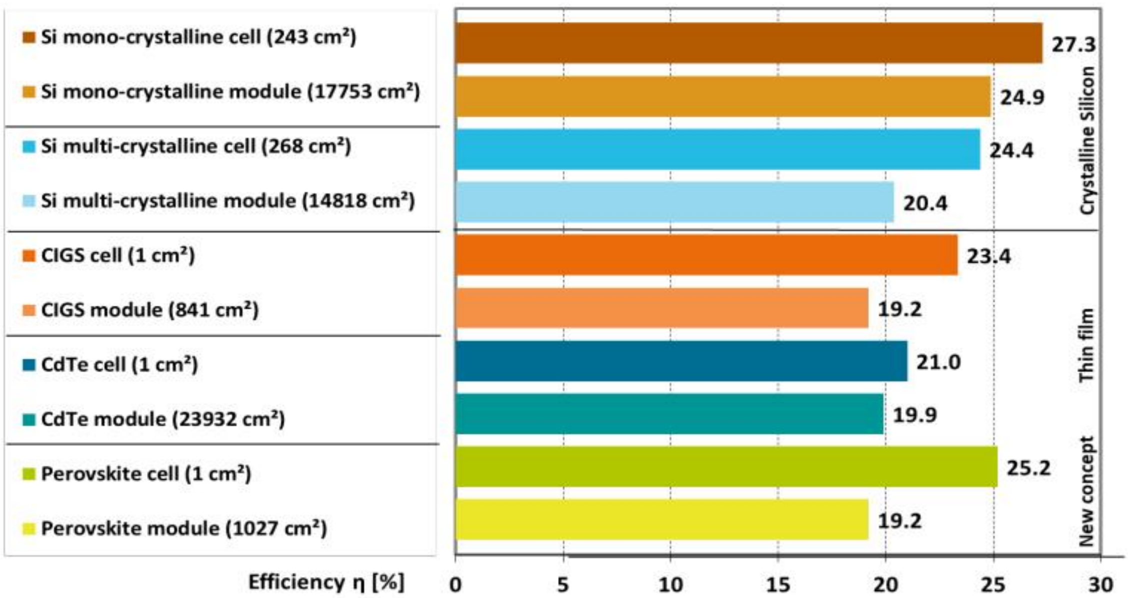

Figure 4. Efficiency Comparison of Technologies; Best Lab Cells vs. Best Lab Modules (Source: Data: (Green et al., 2024). Graph: PSE Projects GmbH 2024. Month & Year of data: 06/2024).

Based on the most recent data from the indicated source in the figure caption, Figure 4 illustrates the efficiency comparison between the best laboratory cells and the best laboratory modules based on technology. During recent years, the cell-to-module ratio (CTM) in mass production has seen improvement through decreased losses and increased utilization of potential gains from solar cell integration into modules.

Types of Photovoltaic Cells:

Thin-Film Photovoltaic: A thin-film solar cell is created by applying thin layers of PV material onto a substrate such as glass, plastic, or metal. Currently, two primary kinds of thin-film PV semiconductors are available for purchase: cadmium telluride and copper indium gallium selenide (CIGS). Both materials can be applied directly to the front or back of the module surface. CdTe, the second most prevalent photovoltaic material following silicon, can be manufactured into cells using affordable processes. Although this factor makes them a cheaper option, their efficiencies need to match up to those of silicon. CIGS cells possess ideal characteristics as a PV material and demonstrate high efficiencies in the laboratory setting. Yet, the intricacy of incorporating four elements complicates the shift from lab scale to mass production. CdTe and CIGS need more protection than silicon to ensure extended durability when utilized outdoors.

Perovskite Photovoltaic: Perovskite solar cells are a thin-film cell type named after its unique crystal structure. Perovskite cells consist of layers of materials that are applied through printing, coating, or vacuum deposition onto a base layer known as the substrate. Typically, they are simple to put together and can achieve efficiencies on par with crystalline silicon. Perovskite solar cell efficiencies in the lab have increased more rapidly than any other PV material, rising from 3% in 2009 to 25% in 2020. To be economically feasible, perovskite PV cells must last outdoors for 20 years, prompting scientists to improve their durability and create inexpensive manufacturing methods on a large scale.

Organic Photovoltaic: Organic photovoltaic (OPV) cells consist of carbon-rich compounds and can be customized to improve a specific PV cell function, like bandgap, transparency, or colour. OPV cells are currently half as efficient as crystalline silicon cells and have shorter lifetimes, but they may be cheaper to produce in large quantities. OPV can also be used with a range of supporting materials, including flexible plastics, which makes it versatile for many different purposes.

Quantum Dots: Quantum dot solar panels generate electricity by utilizing minuscule semiconductor particles known as quantum dots, which are only a few nanometres in size. Quantum dots offer a novel method for handling semiconductor materials, yet establishing an electrical link between them is challenging, resulting in lower efficiency levels. They can be applied to a surface through spin-coating, spraying, or roll-to-roll printing methods, similar to those utilized in newspaper printing. Quantum dots are available in different sizes and can have their bandgap adjusted, allowing them to absorb light that is hard to capture and be combined with other semiconductors, such as perovskites, to enhance the efficiency of a multijunction solar cell.

Multijunction Photovoltaic: An additional approach to enhance the efficiency of PV cells involves stacking various semiconductors to create multijunction photovoltaic systems. These cells consist of stacks of various semiconductor materials, unlike single-junction cells that contain just one semiconductor. Every layer possesses a distinct bandgap, enabling them to capture varying sections of the solar spectrum and utilize sunlight more efficiently than single-junction cells. A solar cell with two bandgaps is called a tandem solar cell, although all solar cells with multiple bandgaps are categorized as multijunction solar cells. Multijunction solar cells have shown efficiencies exceeding 45%; however, their production is expensive and complex, making them suitable only for space missions.

Concentration Photovoltaic: Concentration PV, or CPV, directs sunlight onto a solar cell through a mirror or lens. Focusing sunlight on a small area reduces the amount of PV material needed. PV materials show increased efficiency with higher light concentration, making CPV cells and modules achieve the highest efficiencies overall.

Applications:

There are various applications in diverse fields, like

- as a power source for the International Space Station, Earth-orbiting satellites, etc.
- as a power source in remote areas
- as an alternative energy source in the home, industrial sectors, etc.
- in vehicles, it acts as auxiliary power devices
- in devices like calculators, solar chargers, solar pumps, etc.
- In military uses.

Worldwide Progression Status and India Government Policy:

With the world recognizing the importance of sustainable energy solutions, governments around the globe are introducing different incentives to encourage the use of solar power. These incentives aim to promote investment, lower costs, and accelerate the implementation of solar power facilities. Figure 5 (source of data provided in figure caption) shows that annual production has grown by a factor of 13 in the last ten years. Around 95% of solar modules and their parts were sourced from Asia in 2023, mainly from China. China has an 80% share in module production and dominates over 95% of the market for specific components like ingots and wafers. Figure 6 shows a significant increase in grid connection over time. Presently, around 99.6% of the PV capacity that has been installed is linked to the grid. The percentage of off-grid systems has decreased by around half over the years, dropping from almost 1% in 2010 to 0.43% in 2023. Figure 7 guarantees the enhancement of various types of solar cell efficiencies over time due to progress in research and technology. By 2023, China held the top globally, with a 35.6 % share of solar energy consumption. During that time, the US was responsible for about 14.7% of global solar consumption, positioning it as the second biggest solar power consumer on a global scale. In India, there has also been a notable rise in the utilization of PV, making up around 7% of the total PV capacity worldwide. Figure 8 clearly illustrates the year-wise cumulative PV Installation, with the data source provided in the figure caption.

To promote sustainable development and the welfare of the people, the Ministry of New and Renewable Energy, Government of India, has launched the PM Surya Ghar: Muft Bijli Yojna. Rupees 75000 crore has been allocated to illuminate one crore homes by supplying up to 300 units of complimentary electricity. The Indian government is introducing the Production Linked Incentive (PLI) Scheme for the National Programme to boost efficient modules' solar PV manufacturing capacity, introduce advanced technology in India for producing high-efficiency modules, and encourage establishing integrated plants for improved quality control and competitiveness. The goal is to create a system for obtaining materials locally for solar manufacturing, increase employment and achieve technological independence.

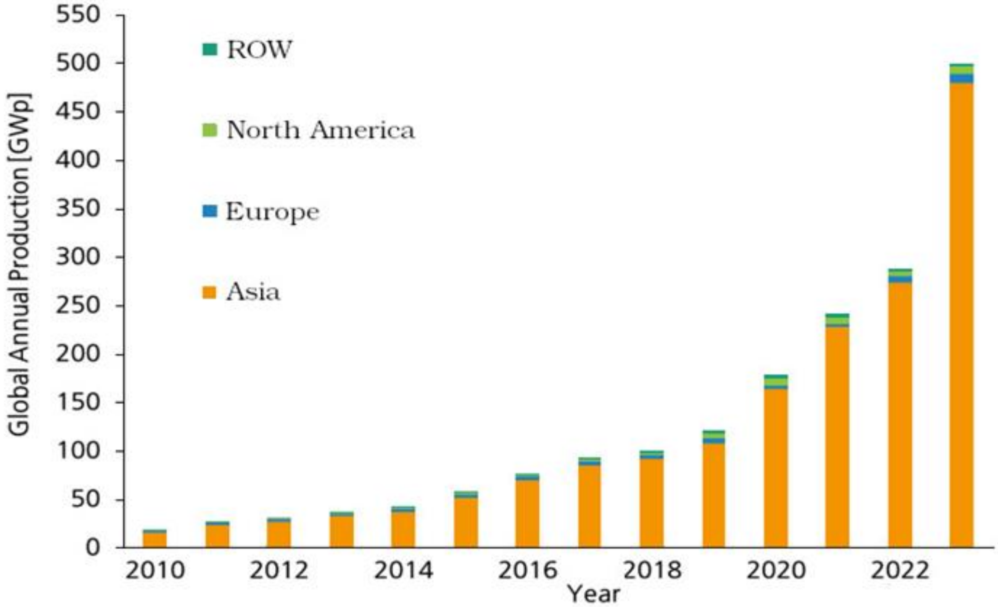

Figure 5. PV Module Production by Region (Source: Data: from 2010 to 2021 IHS Markit from 2022 estimates based on IEA and other sources. Graph: PSE Projects GmbH 2024. Month & Year of data: 04/2024).

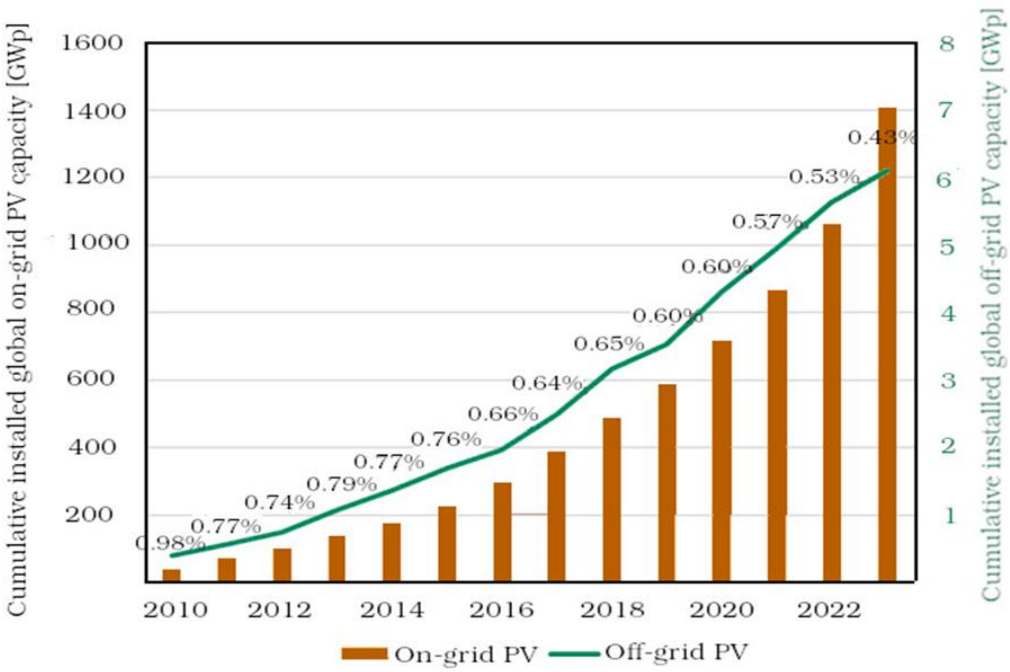

Figure 6. Global Cumulative PV Installation by on-grid & off-grid installation type (Source: Data: IRENA 2024. Graph: PSE Projects GmbH 2024. Month & Year of data: 04/2024).

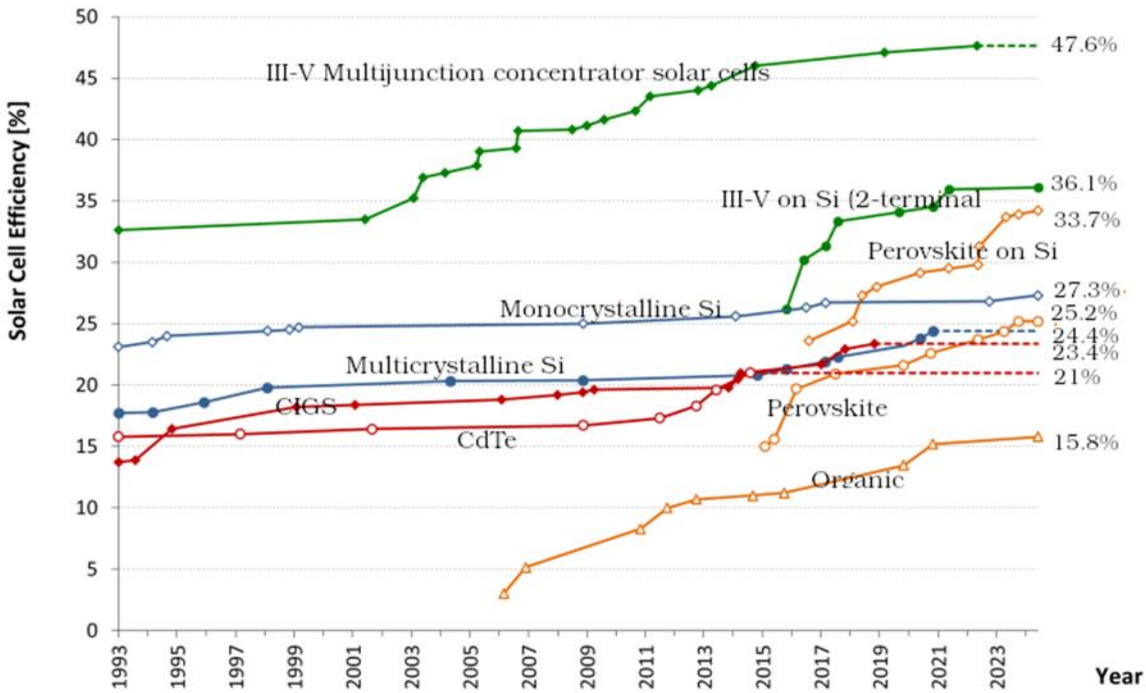

Figure 7. Development of Laboratory Solar Cell Efficiencies (Source: (Green et al., 2024), 1993-2024. Graph: Fraunhofer ISE 2024. Date of data: 06/2024).

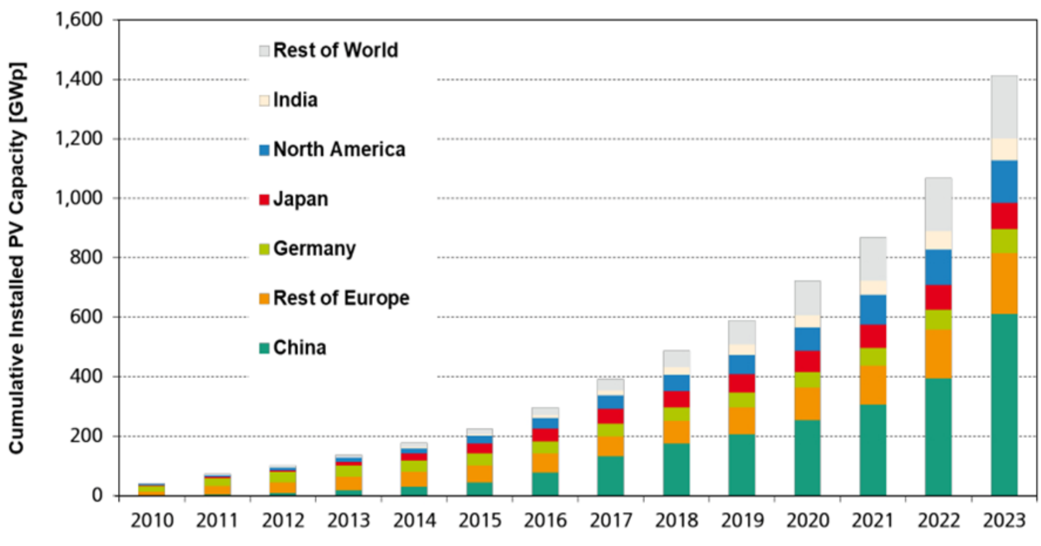

Figure 8. Global Cumulative PV Installation year-wise (Source: Data: IRENA 2024. Graph: PSE Projects GmbH 2024. Month & Year of data: April-2024).

Advantages and disadvantages of photovoltaic systems:

Advantages	disadvantages
• Renewable and Sustainable energy source • cost-effective in the long run • Flexible and highly reliable • Low maintenance cost • Long life span • Zero fuel consumption • safe in use • Energy independence	• Initial or startup cost is high • Weather dependent • Required external energy storage device • Constraints of sufficient space • Scarcity of materials • Difficulties in relocation • Recycling or disposal issues

Conclusion:

Photovoltaic (PV) is a simple and fashionable method of harnessing solar energy. Photovoltaic devices or solar cells can directly transform sunlight into electricity without creating noise or pollution or needing moving components, guaranteeing their long-lasting and dependable nature. This article explains how solar cells are based on the same principles and materials as the communications and computer industries and discusses how photovoltaic devices work and their various applications. Photovoltaic popularity relies on cost, raw material availability, and efficiency. Research is currently being conducted to find new materials for solar photovoltaic devices. The goal is to identify a system with high efficiency, reduced cost, and enhanced durability. Current data shows worldwide the continuously increasing rate of use of solar cells and the improvement of efficiency of solar cells. For the sustainable development of society, it is essential to transition to solar energy as a more environmentally friendly power source.

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Chapter- 9

Tri-County Disparities in Hilsa Conservation Management Reveal Varying Approaches Among India, Bangladesh and Myanmar

Labanya Sarkar*, Rinku Pati, Moumita Mahato, Shampa Mandal and Ashim Kumar Nath

Keywords: Disparity, Conservation, Sustainability, Tri-country

Abstract:
The Hilsa is a valuable, migratory fish species in the rivers, estuaries and coastal regions of India, Bangladesh and Myanmar. However, these bistate conservation partnerships across these three nations have revealed inconsistencies in the approaches to conservation management as influenced by their policy systems, legal instruments and actors' agendas. This study explores the changes in the three-counties' conservation efforts with regard to the Hilsa fish; these include: protection of its natural habitat, regulation of fishing activity and involving the community. While Bangladesh has taken strong regulatory approaches such as seasonal closure and no take zones, India continues to support community-based approaches and context-oriented co-management strategies. Myanmar, on the other hand has been found to have 'low regulatory enforcement' thereby denying conservation efforts required impetus. These disparities are further conditioned by socio-economic differences, and with reference to Hilsa fisheries especially, differences in dependence on this fish resource for food and income. From 2010 to 2015, estimates show that Bangladesh accounted for the largest Hilsa fish catch at 86.7%, followed by India at 8%, and Myanmar at 4%. Various natural and man-made factors currently hinder Hilsa fishing and threaten its future sustainability, necessitating immediate intervention. This manuscript examines the efforts undertaken by India, Bangladesh and Myanmar to ensure the sustainability of Hilsa fishing, along with their future strategies for control and enhancement.

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Introduction:

Hilsa (*Tenualosa ilisha*), an anadromous fish belongs to clupeids family with reference to Sardines and Herrings (Royce, 1996). It is one of the most important species in marine fisheries along the Bay of Bengal, Indian Ocean, Arabian Sea, and the Persian Gulf Suresh (2017). In 2010–2015, 86.7% of Hilsa production was reported by Bangladesh, followed by India (8%) and Myanmar (4%). Most of the Hilsa fish found in India is produced from the Hooghly-Bhagirathi fishery area in West Bengal. Hilsa fisheries hold a significant socio-economic importance in these areas; they directly engage 2.5 million people in Bangladeshi fisheries sector and still provides 50% of average household animal protein in Myanmar, and it greatly entitled to Myanmar's economy where the marine fisheries continuously lay the fifth largest proportion in its GDP and foreign exchange earnings (DoF; 2018). Marine fish production has continually increased, but per capita fish consumption has gone down due to factors such as population increase and effect on the environment. This underlines the nervous urgency of sustainable Hilsa stock which was threatened by habitat degradation, overfishing and lack of proper regulation.

Nowadays, the rate of Hilsa catch in inland fisheries in the three countries mentioned above is going down, and it has caused concern in the domestic economy (Rahman et al., 2000; Amin et al., 2001; Haldar et al., 2001; Mazid, 2001; Rahman et al., 2001; Amin et al., 2002; BOBLME, 2015b; Suresh et al., 2017). For this purpose, the BOBP-IGO (Bay of Bengal Programme Inter-Governmental Organization) on March 14-15, 2008, at the Central Inland Fisheries Research Institute (CIFRI), presented a trilateral (India, Bangladesh and Myanmar) plan for the management of the Hilsa fishery at Barrackpore (Kolkata) and it was considered that a 'Hilsa portal or website' will be developed for the Bay of Bengal region, alongside the establishment of a data collection and compilation mechanism in member countries (Bay of Bengal News, March - June, 2008). Here this review highlights the commendable Hilsa conservation efforts in these three countries, those are essential for the development of the Hilsa fishery sector and the enhancement of economic conditions across the tri-national area.

Current status of the cherished Hilsa and its fishery in the three mentioned countries:

The "queen of fish" Hilsa, given the geographical identification of Bangladesh, is valued not only for its nutrition and taste but also for the economic development and livelihood of millions of people in the Indo-Pacific region (NAAS, 2018).

In India, Hilsa typically lives for up to six years, but due to recent high levels of exploitation of mature female fishes and juveniles, most are caught at two or younger. This accelerated fishing pressure has caused exploitation rates to soar from 0.37 to 0.81 since 2012, indicating a concerning trend in mortality attributable to fishing activities (Hossain et al., 2019). The annual capture of juvenile hilsa reaches about 38 tonnes, valued at Rs. 0.15 crores, translating to a yearly loss of approximately Rs. 76.95 crores if these fish were allowed to grow for one year to attain a size of 250-300 grams within the Hooghly-Bhagirathi River system (Suresh et al., 2017). This population decline is primarily attributed to the extensive use of small mesh gillnets (less than 60 mm mesh size), which result in the capture of a significant number of juvenile hilsa, particularly in riverine habitats (Chacraverti, 2021). Although large-sized (61.4 cm) Hilsa were caught in the Tapti River in Gujarat, it was marked as highly exceptional (Bhaumik et al., 2012).

In Myanmar, Hilsa is renowned for its high market value, driven by solid and consistent demand from export markets, especially in India and China (BOBLME 2015a). Besides, small-scale fishers in the Ayeyarwady region heavily depend on Hilsa catches as a significant income source (Soe et al., 2018). Here, the offshore vessels account for the majority (55%) of the Ayeyarwady Region's Hilsa catch, with the remainder coming from artisanal fishers who use boats and fixed traps in both freshwater and inshore marine waters, managed collectively (DoF, 2019). Despite Myanmar's tendency to over-report capture fisheries statistics, this discrepancy is likely influenced by the belief that certain inland capture fisheries, such as the Hilsa fishery, yield approximately 50% more fish than officially recorded — commonly known as the 'hidden harvest' (Kelleher et al., 2012).

Rivers that are fundamental to the three-nation hilsa fishery:

Many rivers (Fig.1) of the three countries are associated with the hilsa fishery; those are mentioned below.

In India, on both the west coast in rivers like Narmada (Kulkarni, 1950), Tapti / Tapi, and Purna, and the east coast in waterways such as Hooghly-Bhagirathi, Brahmaputra, Krishna, Kaveri, and Godavari, Hilsa are plentiful.

In Bangladesh, the abundance of Hilsa is mainly centered on the Padma, Meghna and Brahmaputra rivers.

On the other hand, In Myanmar, the Ayeyarwady riverine Delta as well as the adjacent Rakhine State and possibly also Mon State (Baran et al. 2017), is crucial for Hilsa fishing, as it targets the spawning and nursing grounds of the Hilsa shad (*Tenualosa ilisha*, locally known as Nga Tha Lauk), fulfilling both local needs and supplying the national market (Belton et al., 2015).

The species of Hilsa (belongs to the genus *Tenualosa)* are widely distributed and visible in all three countries:

In India, out of the five species belonging to the genus Tenualosa of Hilsa i.e., Hilsa Shad, *Tenualosa ilisha* (Hamilton- Buchannan, 1822); Toli Shad, *T. toli* (Cuvier- Valenciennes, 1847); Longtail Shad, *T. macrura* (Bleekar, 1852), Reeve's Shad, *T. reevesii* (Richardson, 1846) and the Laotian Shad, *T. thibaudeaui* (Durand, 1940) only two species [1. *Tenualosa ilisha* and 2. *Tenualosa toli* (Fig.2)] are observed (FAO, 1974), of which *Tenualosa ilisha* is used for various research purposes in India (Pillay, 1958).

On the other hand, *Tenualosa ilisha* is also noticeable in Bangladesh and Myanmar (Blaber et al., 2001).

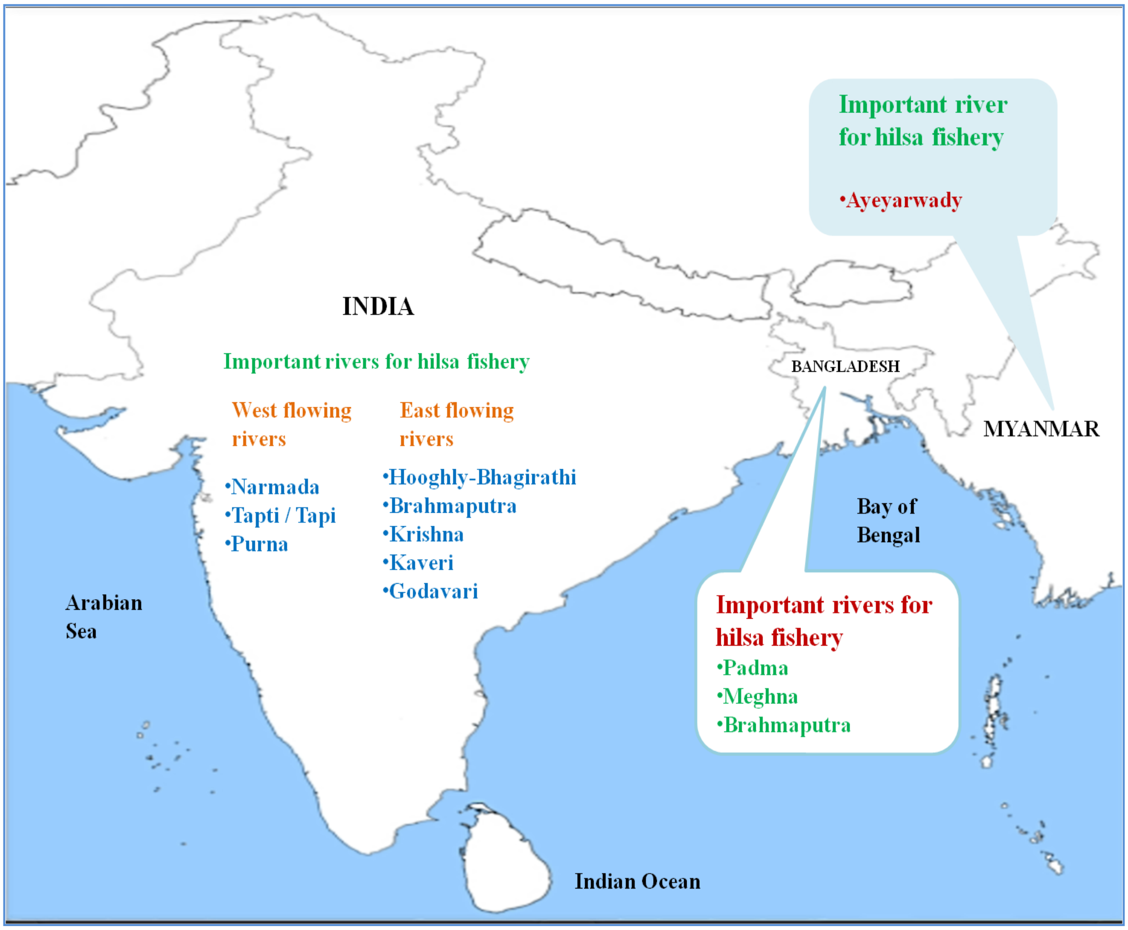

Figure 1. Tri-national (India, Bangladesh and Myanmar) map with names of essential rivers in the Hilsa fishery.

Comparative analysis of the Hilsa spawning seasons in the three countries:

Hilsa undertakes migrations from the sea to freshwater rivers specifically for spawning. This migration pattern supports the survival of Hilsa larvae and plays a crucial role in the species' reproductive success and population dynamics (Bhaumik and Sharma, 2012). So, determining the spawning season of Hilsa is particularly important in Hilsa conservation because the stricter the halt on Hilsa fishing during this period, the more significant its survival rate increases. This spawning season of Hilsa is highly dependent on its ecosystem. Therefore, different scientists have described this period in other ways, as mentioned below.

In India, the peak spawning season of Hilsa is mainly in monsoon (Hora and Nair, 1940a; Kulkarni, 1950; Jones and Sujansingani, 1951; Karamchandani, 1961) and winter (Jones and Menon, 1951; Sujansingani, 1957). However, in some cases, Hilsa can be seen spawning in other months and even throughout the year (Raja, 1985).

After reading various articles, it is clear that in Bangladesh, there are basically two spawning seasons of Hilsa, one is the monsoon (Ahmed, 1954; Raja, 1985) and the other is the post monsoon (Islam et al., 1987).

In Myanmar, the Hilsa spawning season is observed three times a year. August to September marks the principal spawning period for Hilsa in the Ayeyarwady Delta, with additional spawning likely occurring during January to February and April to May (Bladon et al., 2019).

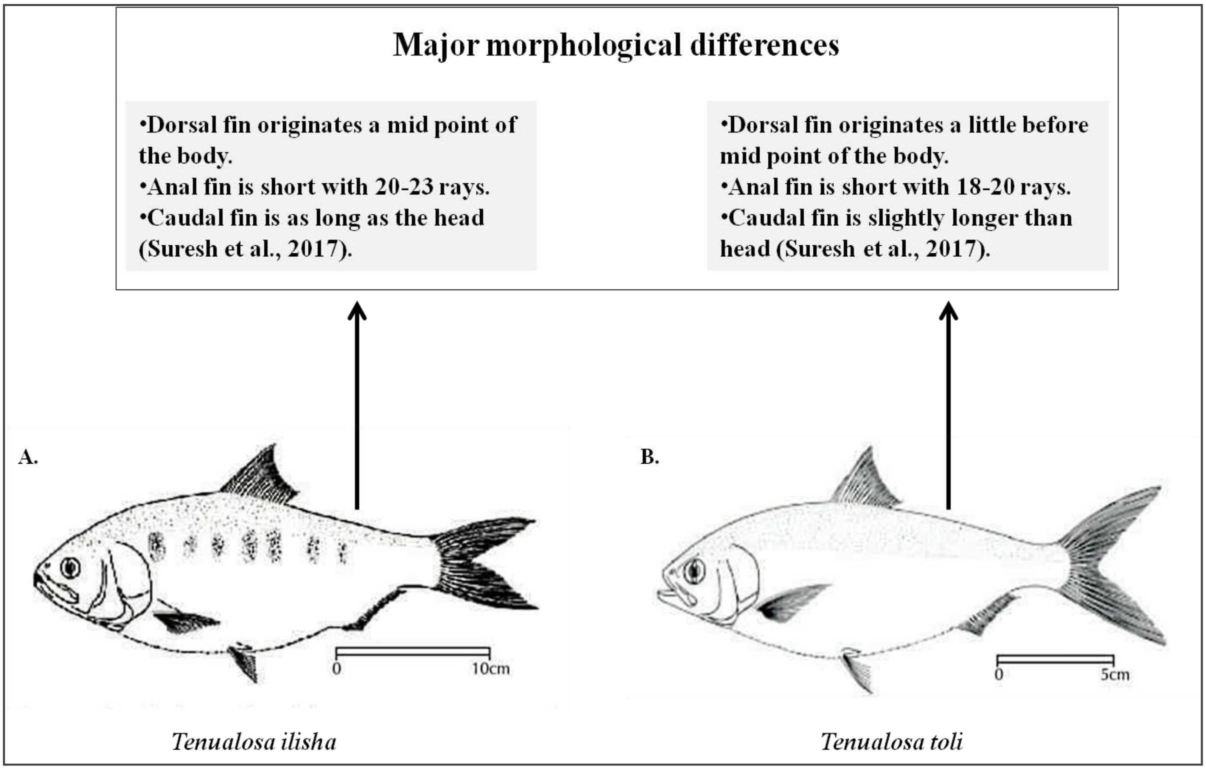

Figure 2. Sketch of A. *Tenualosa ilisha* and B. *Tenualosa toli* (Source: FAO, 1974) with their significant morphological differences.

What? Variables that could affect the future viability of the Hilsa fishery:

Hilsa undertakes migrations from the sea to freshwater rivers specifically for spawning. This migration pattern not only supports the survival of Hilsa larvae but also plays a crucial role in the species' reproductive success and population dynamics (Bhaumik and Sharma, 2012). But, In India, the installation of barrages and dams along major east and west coast rivers, especially the Hooghly - Bhagirathi [like Farakka barrage (De et al., 1994)] and Narmada, has blocked the Hilsa's migratory paths to their breeding habitats in the upper stretch of riverine zones, causing the Hilsa fisheries in these rivers to collapse (Nair, 1958), as a result, Hilsa landing at estuarine zone can be observed more (Raja, 1985). In addition, both in India and Bangladesh, the indiscriminate use of Hilsa nets with a small mesh size that is less than 60mm (Chacraverti, 2021), as well as the natural and man-made physico-chemical changes in sea and river water, are hurting the future survival rate of hilsa.

In Myanmar, there is a disproportionately high pressure on the freshwater fishery because Hilsa caught in freshwater are more likely to include juvenile fish and mature female fish with ripe gonads, which are often targeted during their spawning runs (Khaing et al., 2019). Due to their seasonal inland migration, Hilsa is vulnerable to threats from land-based activities such as habitat destruction and water contamination (BOBLME, 2015b). That means the key factors influencing the sustainability of Myanmar's Hilsa fishery include overfishing of juveniles and brood female Hilsa using small-mesh nets (BOBLME, 2015c) and habitat destruction, compounded by water pollution and climate change (BOBLME, 2015b; Baran et al., 2017; Khaing et al., 2018).

Who? Will ensure the future sustainability of the Hilsa fishery:

The effectiveness of livelihood-focused development interventions often hinges on carefully implementing alternatives, compensation mechanisms, and incentive structures (Wright et al., 2016). Practical alternative livelihood aims to bolster conservation by diversifying income streams and reducing the necessity for natural resource exploitation (Roe et al., 2015). On the other hand, the effectiveness of incentive schemes hinges on their ability to offer tangible resources as encouragement, particularly when behavioral adjustments do not align with agreed-upon criteria (Wunder, 2013).

But in India, no such incentive has been arranged for fishers. So, the ban period is not given that importance in Hilsa fishing. Several fishery-oriented institutions have been working for Hilsa conservation for a long time. For example - In 2012, the Indian Council of Agricultural Research (ICAR) initiated the first comprehensive study for ensuring the future sustainability of the Hilsa fishery on "Stock characterization, captive breeding, seed production, and culture of Hilsa (*Tenualosa ilisha*)" under the National Agricultural Science Fund (NASF). Subsequently, Central Inland Fisheries Research Institute (CIFRI) spearheads this effort in collaboration with other ICAR fishery institutes and the University of Shantiniketan, West Bengal (Annual Report of CIFRI, 2016). Besides, various schemes seem to be implemented for fishermen [like the recent 'Samudra Sathi Scheme' in West Bengal, whereby workers engaged only in fishing across sea will receive INR 5000/- only per head per month for two months i.e. May and June (Sinha, 2024)] are challenging to implement promptly and none of these are Hilsa fishing focused because in this case the ban period of Hilsa fishing is not given importance. On the other hand, some traditional customs prevalent among Bengalis play a unique role in Hilsa conservation. For example, Bengalis traditionally eat a pair of Hilsa (locally known as 'Joda Ilish') on the day of 'Vijaya Dashami' (usually in October) and then do not eat Hilsa fish until Saraswati Puja (usually February), resulting in relatively less Hilsa catch during this primary spawning season of Hilsa (Suresh et al., 2017).

In Bangladesh, ban periods on Hilsa fishing are strictly observed. The annual eight-month ban on fishing activities, including selling juvenile Hilsa fish, spans from November 1st to June, covering extensive riverine, estuarine and coastal regions totalling 7,000 square kilometres (Nishat et al., 2019). On the other hand, the country-wide ban on fishing for gravid Hilsa reflects a proactive approach to fisheries management, emphasizing the importance of protecting critical breeding periods for 22 days i.e., 14th October to 4th November (Rahman et al., 2017). The provision of 10 kg of rice bi-monthly and, in some cases, amounts by the government during the early phase of the Hilsa sanctuary ban aimed to alleviate food insecurity among impacted populations. However, the current compensation framework is aimed solely at Hilsa fishers and overlooks the broader impact on other fishers whose livelihoods are similarly disrupted during ban periods (Bladon et al., 2016).

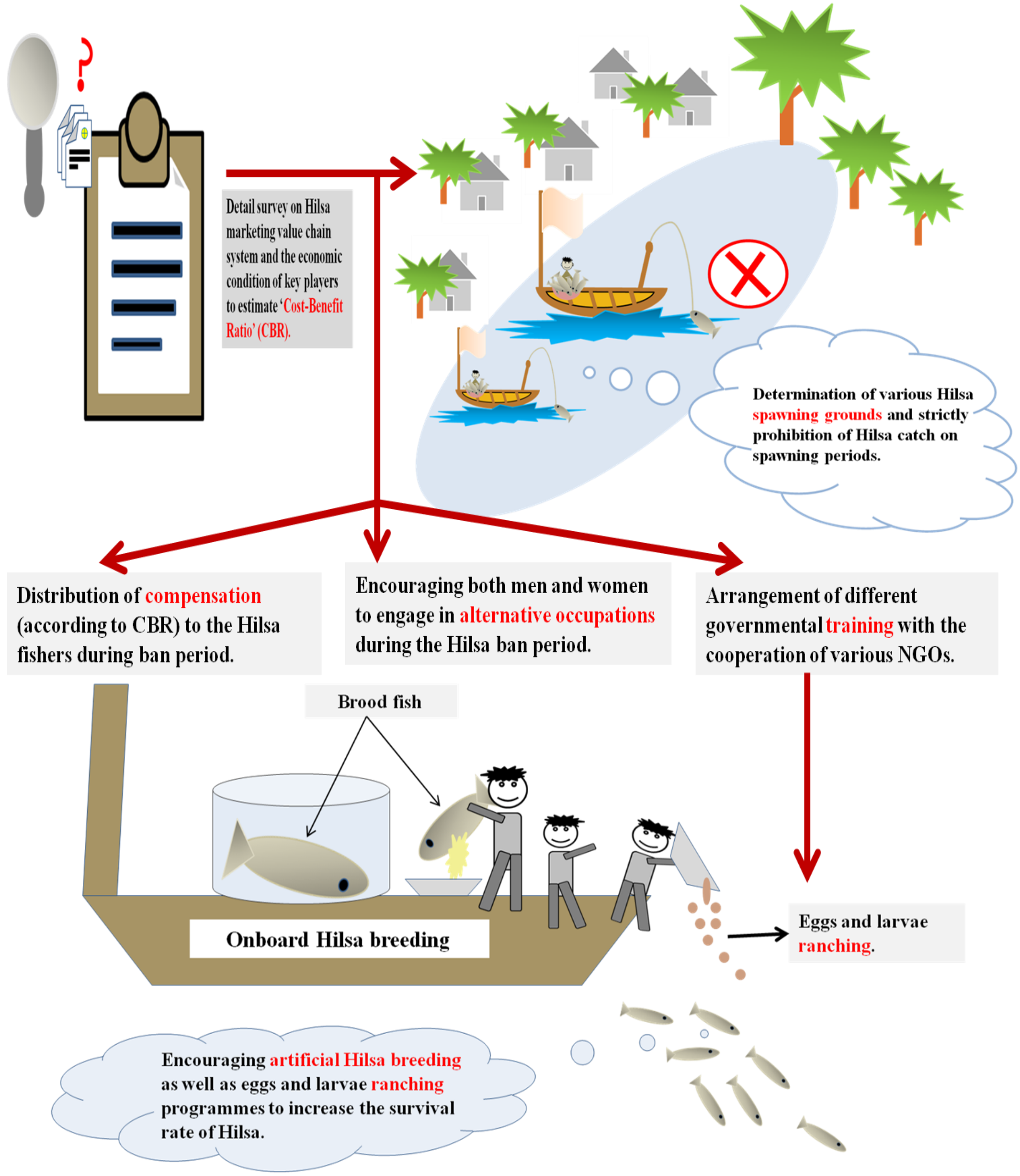

Figure 3. Proposed plans for the future conservation of Hilsa and its fishery sector.

Policymakers are considering incentive-based conservation strategies in Myanmar to promote sustainable hilsa fishing practices. These approaches resemble 'payments for ecosystem services' that involve providing economic incentives to encourage compliance with current and future fishing regulations. By compensating fishers for any losses resulting from regulatory measures, these schemes are expected to foster greater adherence and sustainability than purely punitive enforcement methods (Bladon et al., 2018). National and regional regulations [Freshwater Fisheries Law (1991) and Marine Fisheries Law (1990)] play a critical role in safeguarding Hilsa and other commercial fish species; for instance, freshwater and inshore marine fisheries are closed annually from May to July to preserve spawning grounds and support recruitment. Although these implementations were initially slow, progress has been steady with increased awareness and community participation (Tezzo et al., 2018).

Conclusion:

Hilsa fishing and its fisheries have a significant role in the domestic economy and lifestyle of the residents of the three countries. So, it is our responsibility to make the Hilsa fishery sustainable. In this case, Bangladesh government has taken various measures more strictly than the other two countries (specifically, than India), so we need to implement the following plans (Figure 3) for their accurate assessment, which will be able to make the Hilsa fishery sustainable.

At first, a detailed survey on the Hilsa marketing value chain system and the economic condition of critical players to estimate the 'Cost-Benefit Ratio' (CBR) is to be done. Then, various Hilsa spawning grounds are to be determined, and the Hilsa catch on spawning periods and the use of small mesh-sized gears throughout the year are strictly prohibited. Besides, compensations (according to CBR) should be distributed to the Hilsa fishers during the ban period, and they should be given training on breeding and ranching of Hilsa. Last but not least, both men and women are to be encouraged to engage in alternative occupations during the Hilsa ban period.

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Chapter- 10

Symbiotic Relationship of Nemertea: A Comprehensive Review

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Keywords: Community structure, Commensalism, Ecosystem, Nemertea, Symbiosis

Abstract:
Ribbon worms, or Nemertean's, are found in both freshwater and marine environments, where they display a wide variety of symbiotic connections. These relationships have a distinct impact on ecosystem dynamics and species interactions, including mutualistic, commensal, and parasitic relationships. The numerous symbiotic interactions involving Nemerteans are reviewed in this paper, with particular attention paid to their ecological functions, impacts on host animals and consequences for biodiversity and community structure. By scrutinizing contemporary literature and case studies, we underscore the intricacy and importance of Nemertean symbiosis and pinpoint domains that warrant further investigation.

Introduction:

Marine ecosystems are characterized by symbiosis, which includes parasitism, commensalism, and mutualism (Roughgarden, 1975; Margulis, 1991). Numerous animals have undergone morphological and ecological diversification due to these symbiotic connections, which alter the symbiont species' anatomy, physiology, and reproductive systems (Sotka, 2005; Joy, 2013). In commensal partnerships, in which symbionts inhabit the host's body, the hosts provide a home for the symbionts to dwell in for some or all of their lifetime.

Nemertea, or ribbon worms, is a phylum of Lophotrochozoa (Kocot et al., 2017; Laumer et al., 2019; Bleidorn, 2019). These soft-bodied, unsegmented worms are differentiated by an

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eversible proboscis located in a fluid-filled chamber known as the rhynchocoel (Gibson, 1982). There are currently roughly 1,350 species of Nemerteans (Hookabe et al., 2024), the majority of which live in maritime benthic settings. They usually live as free-living macrophagous carnivores, feeding on polychaetes, molluscs, and small crustaceans, or as scavengers (McDermott et al., 1985).

However, at least 50 Nemertean species have been shown to have symbiotic interactions with other creatures (Jensen and Sadeghian, 2005; Junoy et al., 2010; Sadeghian and Santos, 2010; Kajihara and Kuris, 2013; Simpson et al., 2017). Bivalves, crustaceans, and ascidians are the most diverse groups of invertebrates that host symbiotic Nemerteans. The majority of known symbiotic Nemertean species are found in the class Hoplonemertea, suborder Eumonostilifera, which includes 11 genera and two families (Malacobdellidae and Carcinonemertidae) that are entirely made up of symbiotic species.

Their associations with other organisms vary from mutualistic to parasitic, demonstrating their versatility and evolutionary success. Understanding these symbiotic connections is critical for understanding Nemertean ecology in general. This review summarizes current information about Nemertean symbiosis, focusing on mutualistic, commensal and parasitic connections and their impact on ecosystems.

Symbiotic Relationships:

Association with bivalve:

- *Malacobdella arrokeana* is found in *Panopea abbreviata* (Ivanov et al., 2002).
- *Malacobdella grossa* was discovered in the mantle cavity of the oval Piddock, *Zirfaea crispat*e (Gibson in 1967 and 1968).
- *Malacobdella siliquae* inhabits *Siliqua patula*, while *Malacobdella macomae* inhabits *Macoma secta* and *M. nasuta* (Kozloff 1991).
- *Tetrastemma fozensis*, a tiny hoplonemertine, lives in the mantle cavity of the bivalve *Scrobicularia plana* (Thiel et al., 1997).
- *Uchidana parasite* found in bivalve *Mactra chinensis* (Dieck, 1874).
- *Malacobdella japonica* is present in the mantle cavity of *Pseudocardium sachalinense* (Hookabe et al., 2024).

Association with crustacean:

- *Nemertopsis quadripunctata* and *Nemertopsis mitellicola* are found in the goose-neck barnacle *Capitulum mitella* (Kajihara, 2007).
- *Carcinonemertes kurisi* is found in *Randallia ornate* crabs, while *Carcinonemertes tasmanica* lives in *Dittosa laevis* crabs (Sadeghian and Santos, 2010).
- *Ovicides paralithodis* is a symbiotic egg predator for the red king crab, *Paralithodes camtschaticus* (Kajihara and Kuris, 2013).

- *Carcinonemertes conanobrieni* feeds on the eggs of the Caribbean spiny lobster, *Panulirus argus* (Simpson et al., 2017).
- *Pesudocarcinonemertes homari* are ectoinhabitants of the lobster *Homarus americanus* (Fleming and Gibson, 1981).

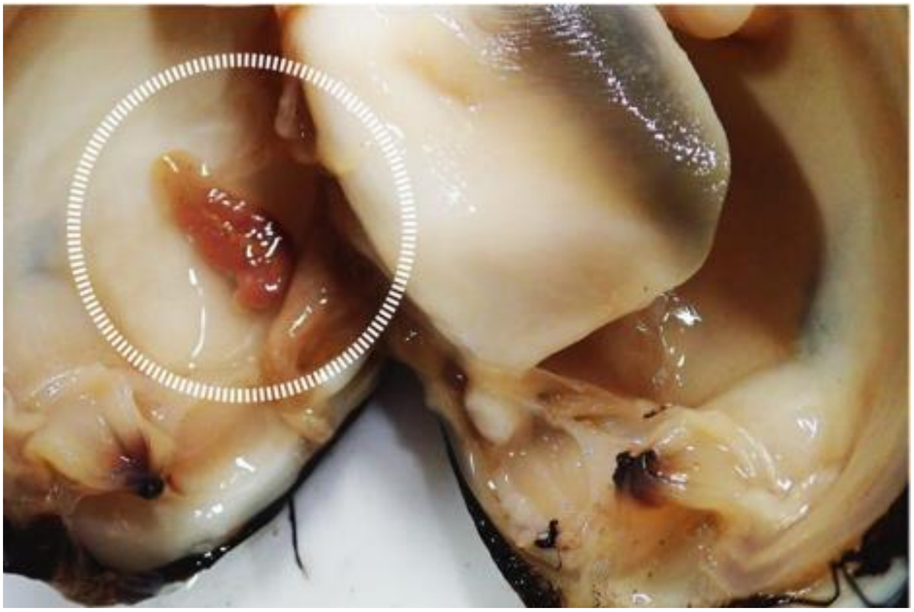

Figure 1. ***Malacobdella japonica*** **is found in the mantle cavity of** ***Pseudocardium sachalinense*** **(Hookabe et al., 2024).**

- *Ovicides jasoni* juveniles or regressed adults were detected in the mucous sheaths of *Austinograea alayseae* crabs.*Ovicides davidi* derives its name from the bythograeid crab *Cyanagraea praedator*. *Ovicides jonesi* are found in *Bythograea vrijenhoeki*, while *Ovicides julieae* suppress *Chlorodiella* spp. (Xanthid crab) (Shields and Segonzac, 2007).
- *Carcinonemertes pinnotheridophila* discovered in the branchial chambers of *Pinnixa chaetopterana*, Decapoda (McDermott and Gibson, 1993).
- *Carcinonemertes divae*, *C. caissarum*, and *C. sebastianensis* are associated with the crabs *Libinia spinosa*, *Hepatus pudibundus*, and *Menippe nodifrons* (Santos et al., 2006).
- *Carcinonemertes regicides* from red king crabs *Paralithodes camtschatica* and *C. errans* affect the Dungeness crab *Cancer magister* (Kuris, 1993).
- *Cephalothrix galatheae is found in the anomuran crab Galathea strigose* (Dieck, 1874).
- *Carcinonemertes camanchaco lives in the Host crab species Romaleon setosum and Cancer porteri* (Leiva, 2021).

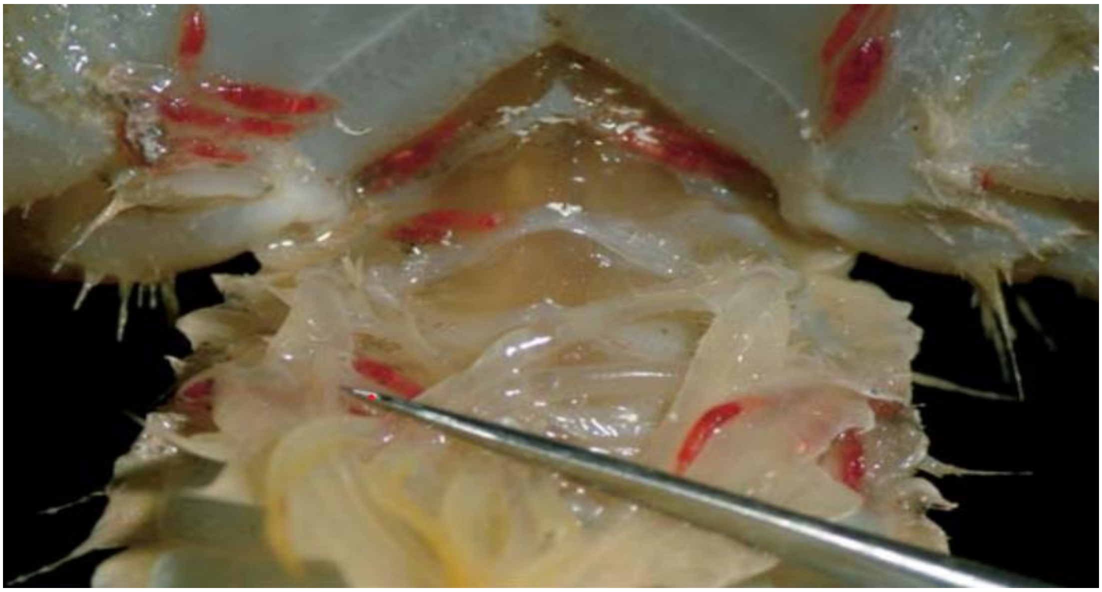

Figure 2. Juvenile worms of *Ovicides jasoni* present on the sternum, pleon, and pleopods of *Austinograea alayseae* (Shields and Segonzac, 2007).

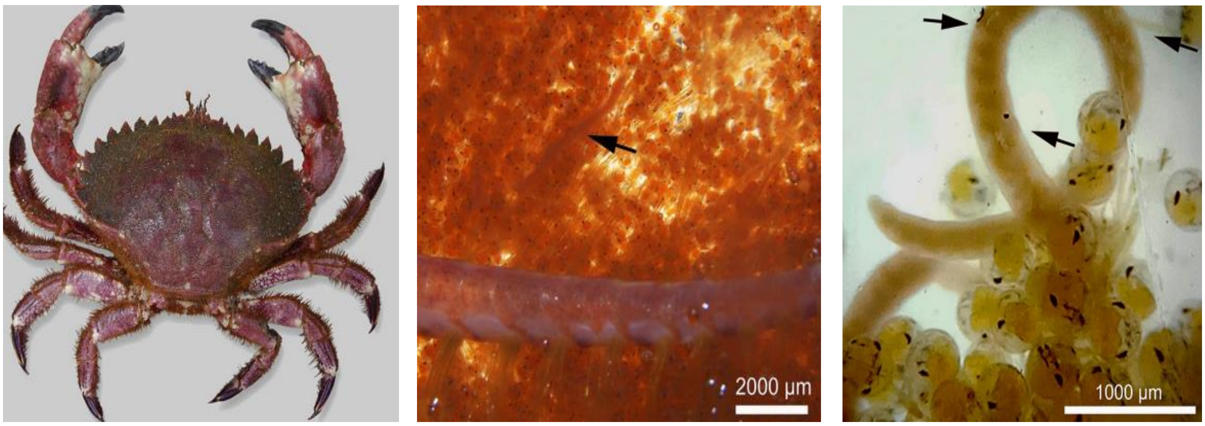

Figure 3. Host crab species *Romaleon setosum* infected by *Carcinonemertes camanchaco* and also present in their egg masses (Leiva, 2021).

Association with Ascidian

- *Gononemertes australiensis* was found in *Pyura pachydermatina*, an ascidian host (Egan, 1984).
- *Vieitezia luzmurubeae* is linked to *Phallusia mamillata* (Junoy et al., 2010).

Association with Echiuran

- *Nemertoscolex parasiticus* is an endoparasitic heteronemertean found in the coelomic fluid of *Echiurus echiurus* (Berg and Gibson, 1996).

Association with Actiniarians

- *Nemertopsis actinophi* is associated with two species of swimming actiniarians: *Stomphia coccinea* and *Stomphia didemon* (Gibson, 1986).

Association with echinoderms

- Eumonostilifera is associated with echinoderms, such as *Asteronemertes commensalis* and *Asteronemertes gibsoni*, which live in the ambulacral grooves of starfish from the Solasteridae and Pterasteridae families (Chernyshev, 1991; Kyao, 1954).
- *Cephalotrichella echinicola* is linked to heart urchins *Metallia spatagus* and *M. sternalis* (Britayev et al., 2018).

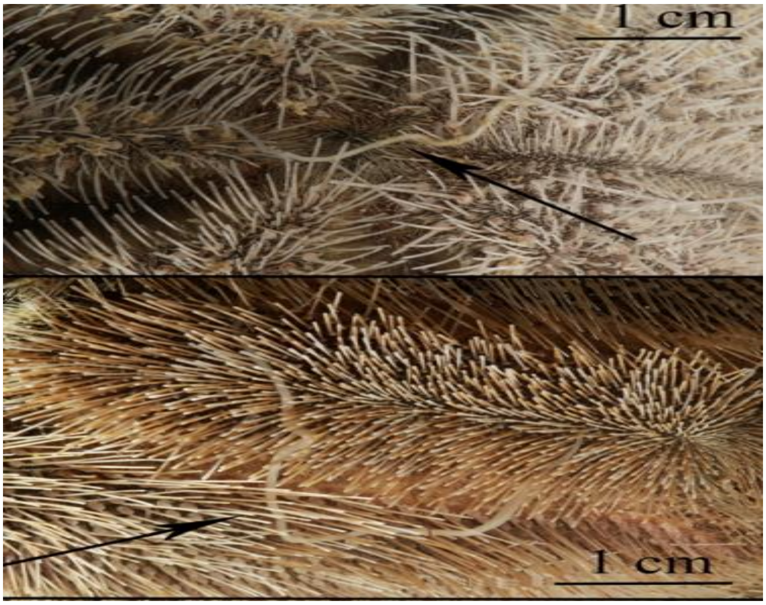

Figure 4. ***Cephalotrichella echinicola*** **is associated with heart urchins (Britayev et al., 2019).**

Ecological Implications

Effects on Host Behaviour and Fitness

The effect of Nemertean symbiosis on host behavior and fitness varies with the nature of the interaction. Hosts who have commensal Nemerteans may demonstrate behavioral modifications to accommodate their symbionts. For example, bivalves that host Nemerteans may change their eating patterns to accommodate their presence. Fitness effects are particularly noticeable in parasitic partnerships when Nemerteans can lower the host's growth rates, reproductive success, and overall health. Commensal and mutualistic partnerships have less severe consequences, and hosts frequently profit from the encounter.

Impact on the Community Structure

Nemertean symbiotic partnerships can have an impact on overall community dynamics by changing species interactions and composition.

The presence of parasitic Nemerteans can decrease the host population, which impacts predator-prey dynamics and resource availability for other species. Commensal Nemerteans may also impact host species' competitive interactions.

Symbiotic partnerships help increase ecosystem resilience and stability by providing complexity to species interactions. The presence of Nemerteans can improve the diversity and function of marine communities, promoting overall ecosystem health.

Contributions to biodiversity

Nemerteans contribute to the complexity of marine environments through their various interactions with other creatures. Their existence produces new niches and microhabitats, allowing for a broader range of species and ecological processes. Nemerteans are important in nutrient cycling, habitat structure, and food web dynamics. Their interactions with other species assist in keeping the environment balanced and contribute to total biodiversity.

Future Research Directions

To further understand Nemerteans' ecological roles in symbiotic partnerships, future studies should focus on many crucial areas:

Detailed ecological studies

Long-term investigations are required to assess the impact of Nemertean symbiosis on host populations and community dynamics. These investigations should focus on seasonal and regional differences in symbiotic interactions.

Molecular approaches

Advances in genetic and molecular techniques, like DNA barcoding and metagenomics, are crucial for finding and classifying Nemertean species and comprehending their evolutionary links.

Behavioural research

Both observational and experimental investigations are needed to study Nemertean behavior and interactions with hosts. This study will help understand host recognition, attachment, and exploitation mechanisms.

Environmental Impact Assessment

Assessing the effects of environmental changes on Nemertean symbiosis is essential for forecasting future ecosystem dynamics. This includes assessing the impact of pollution, climate change, and habitat loss on symbiotic relationships.

Integrative Approaches

Integrating ecological, molecular, and behavioral studies leads to a complete understanding of Nemertean symbiosis. Collaboration across disciplines will improve our ability to address the problems and possibilities presented by these interconnections.

Conclusion

Nemertean symbiosis is a broad and diverse topic of study that covers relationships ranging from mutualism to parasitism. These connections substantially impact marine ecosystems and provide important insights into evolutionary and ecological processes. Continued research is required to understand the full extent of Nemertean symbiosis and its implications for ecosystem health and management.

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We want to express our deep and sincere gratitude to Santosh Kr. Bera, Sujit Das, and Sourav Bar for their support. We are thankful to Coastal Ecology Research Laboratory for allowing us to do this work smoothly. We are also grateful to UGC and CSIR-HRDG, India for their financial support.

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Chapter- 11

Green Surgery: Pioneering Sustainable Practices in Healthcare

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Keywords: Green Surgery, Environment, Sustainability, Recycling

Abstract:

Green surgery, a concept aiming at improving sustainability in the healthcare industry, has become practically important due to the increasing environmental impact of typical surgical procedures. The following chapter thoroughly examines the environmental issues associated with traditional surgical procedures, such as waste creation, large energy consumption, excessive water use, and the release of harmful chemicals and anesthetics. This book provides fundamental concepts of green surgery, such as material reduction, reuse, and recycling, focusing on energy efficiency, water conservation, and sustainable procurement. A comprehensive analysis of realistic strategies for implementing these principles is provided, emphasising waste management, energy and water conservation, and emission reduction. Furthermore, the chapter discusses the problems and impediments to green surgery, such as institutional opposition, financial concerns, and regulatory limits, and provides solutions to overcome them. This chapter includes case studies and success stories from prominent hospitals that demonstrate new technology and practices that have effectively reduced the environmental impact of surgical procedures. This chapter emphasizes the importance of sustainability in ensuring the long-term well-being of patients and the environment by promoting a collaborative effort to adopt more environmentally friendly surgical practices.

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Introduction:

Definition of Green Surgery

Green surgery, which emerged in recent years, is the conscious use of surgical methods to reduce environmental harm while maintaining the highest standards of patient care (Binda et al., 2023). This method advocates for incorporating sustainable practices into all elements of surgery, such as waste minimization, using energy-efficient devices, and establishing recycling programs in the operating room (Mostepaniuk et al., 2023; Sanabria et al., 2020). Beyond its capacity to minimize healthcare-related carbon emissions, green surgery significantly promotes a healthier environment for present and future generations (Sanabria et al., 2020). Green surgery is an important step in creating a more responsible and environmentally conscious medical practice in today's healthcare system, where sustainability is a fundamental factor (Binda et al., 2023; Mostepaniuk et al., 2023).

Green surgery is critical for effectively tackling the environmental issues that healthcare businesses face, which are generally considered a significant source of waste creation and contamination (Binda et al., 2023). Conventional surgical procedures have a significant environmental impact, as seen by waste generation, water usage, and high energy use (Sanabria et al., 2020). Green Surgery tries to mitigate these repercussions by implementing ecologically sensitive practices such as reusable equipment, energy-efficient technology, and reducing dependence on throwaway plastics (Binda et al., 2023). Green surgery's relevance in the current healthcare scene cannot be overstated, as it aligns with the expanding worldwide focus on sustainability and climate change mitigation. Using Green Surgery principles ensures patient safety and treatment quality while helping healthcare personnel significantly reduce the environmental impact of medical procedures (Binda et al., 2023).

Historical Context

Significant technological and procedural breakthroughs have shaped the development of surgical methods, resulting in better patient outcomes and increased operational efficiency (Silva Filho et al., 2023). However, these findings have resulted in unforeseen repercussions, particularly regarding environmental effects (Chaplin et al., 2020). For example, the introduction of disposable surgical equipment has increased medical waste, even while it helps lower infection risk. The energy-intensive nature of modern surgical technologies and their dependence on nonrenewable resources exacerbates surgery's environmental effect (Binda et al., 2023). Early attempts at sustainability in surgery may be found in actions aimed at reducing waste and encouraging the reuse of specific surgical gear. For example, reprocessing medical equipment—which entails cleaning, sterilizing, and packaging items for future use—arose to reduce the environmental effect of surgical procedures (Chaplin et al., 2020). These first initiatives paved the way for the development of green surgery, as operating room doctors saw the need for more comprehensive, sustainable procedures (Binda et al., 2023; Mostepaniuk et al., 2023).

Green surgery's historical context includes a rising awareness of the healthcare industry's role in global pollution and the need for more sustainable therapies (Sanabria et al., 2020). Green surgery is a well-known research topic because the emphasis on incorporating environmental components into healthcare operations has evolved over the past several decades (Binda et al., 2023). The understanding that environmental health is closely related to human health and that the healthcare industry must reduce its environmental effect has driven this development (Silva Filho et al., 2023). Green surgery has, therefore, grown into a multidisciplinary approach that considers the technical elements of surgical treatments and the broader ethical and environmental implications of medical practice (Silva Filho et al., 2023).

The Environmental Impact of Traditional Surgical Practices

Traditional surgical procedures have long been a foundation of contemporary medicine, providing life-saving treatments and improving patient outcomes in various medical diseases (Harris et al., 2017). However, these approaches have a significant environmental cost, primarily due to trash creation. Surgery has a substantial environmental effect; thus, addressing these concerns becomes more vital as the global healthcare business increases (Richie, 2020).

Waste Production

The massive amount of trash typical surgical procedures produces highlights one of the most critical environmental challenges. Surgical waste includes various materials, each with unique disposal needs that, if not correctly handled, may hurt the environment (Chaplin et al., 2020; Harris et al., 2017; Richie, 2020). The many types of surgical waste may be broadly classified into four categories:

Biomedical Waste: This includes surgical gloves, gowns, sponges, and dressings—anything that has come into contact with patients or biological fluids. Biomedical waste is often polluted and must be treated as hazardous, necessitating particular disposal strategies to minimize environmental contamination and disease transmission (Chaplin et al., 2020).

Sharps Waste: includes sharp instruments like scalpels, needles, and knives. Sharps waste is a major concern for both waste management professionals and medical specialists. Proper disposal in certified containers is critical for minimizing damage and preventing the spread of blood-borne illnesses (Chaplin et al., 2020; Harris et al., 2017).

Pharmaceutical Waste: Anesthetics, disinfectants, and other medications and chemicals used in surgery, add to pharmaceutical waste. Improper disposal of these substances may cause environmental harm, especially in water sources, disrupting ecosystems and endangering human health (Richie, 2020).

General Waste: This applies to nonhazardous objects such as single-use products, disposable equipment, and packaging. Although not inherently harmful, the huge amount of general waste generated during surgery is a serious concern, causing environmental damage and landfill overpopulation (Saver, 2011). Figure 1 has shown different types of hospital wastes and their management strategies.

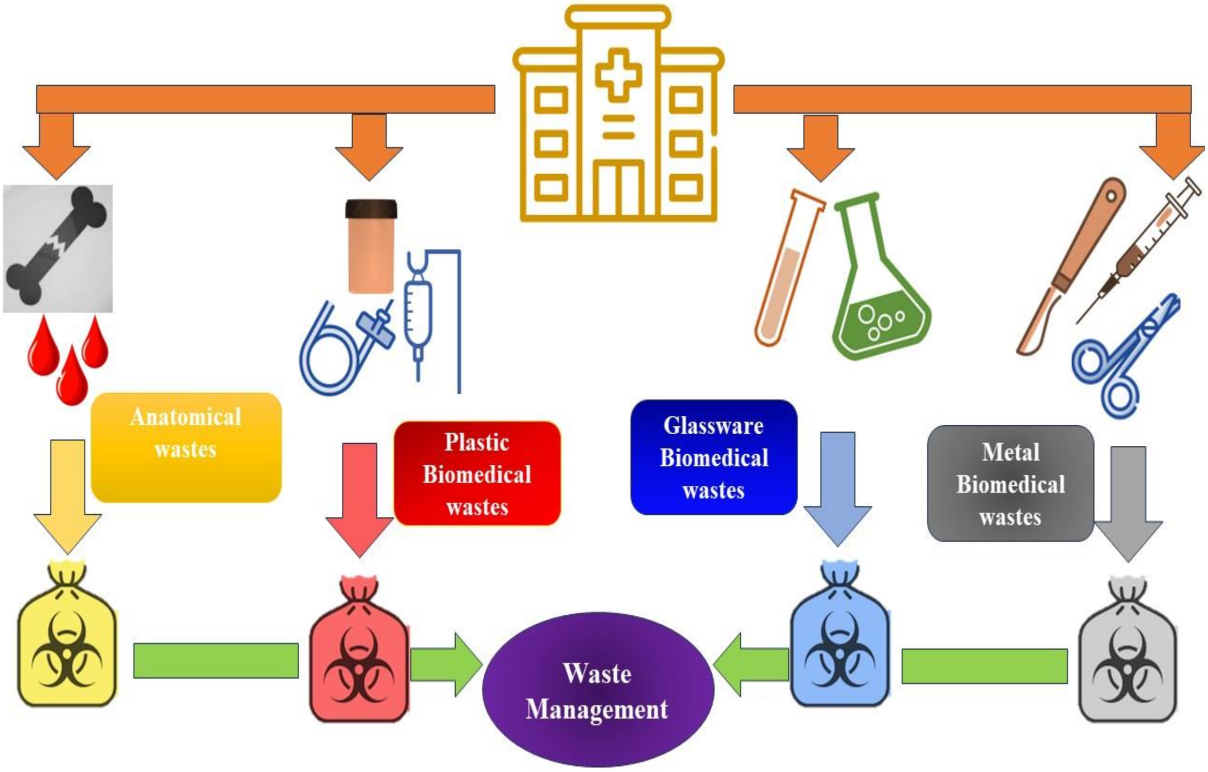

Figure 1. Types of Biomedical Wastes Generated in Hospitals and Their Management Strategies. This figure shows different types of biomedical wastes produced in hospitals and their designated disposal methods. Anatomical wastes (such as body fluids and excised organs) are collected in yellow bags, plastic wastes (such as bottles and catheters) are collected in red bags, glass wastes are collected in blue bags, and metal wastes (such as disposable syringes, scissors, and knives) are collected in white bags. Proper segregation and disposal of these wastes are essential for preventing contamination and ensuring safety.

Statistics on Waste Generation

Typical surgical methods generate astonishingly large volumes of waste. According to the World Health Organization (WHO), 15% of the garbage created by healthcare operations is classified as hazardous material, which may be infectious, poisonous, or radioactive. In contrast, around 85% of the waste produced is non-hazardous (McNamee et al., 2022). However, the nature of the treatments in surgical settings often results in a greater volume of hazardous waste.

Hospitals create an estimated 5.9 million tons of garbage annually in the United States alone, with surgical departments leading the way. Every operation in a conventional operating room may generate up to 20 pounds of trash, most of which consists of single-use items like equipment, gowns, and curtains (Gordon, 2020). These items, often constructed of plastics and other non-biodegradable compounds, cause long-term environmental difficulties when they amass in landfills.

Furthermore, using disposable materials in surgery has exacerbated the waste issue despite its ability to lower the risk of infection (Gorgun et al., 2023). Simple single-use goods have resulted in a culture of disposability, in which items are discarded after one use rather than recycled or repurposed. As a result, surgical waste has grown dramatically, straining waste management systems and contributing to pollution (Yates et al., 2021).

Traditional surgical procedures' environmental effect, particularly regarding waste creation, is an increasing concern worth considering (Westwood et al., 2023). Several forms of surgical waste are created, and their environmental effect may be reduced by proper treatment of each (Goettke et al., 2021). Developing and implementing more sustainable procedures that reduce waste creation and encourage environmental stewardship in surgical settings is critical as the healthcare sector grows (Goettke et al., 2021). By tackling these challenges, the medical community can substantially contribute to environmental preservation while delivering excellent patient care (McGain et al., 2019). Figure 2 shows the distribution of waste generation in surgical practice.

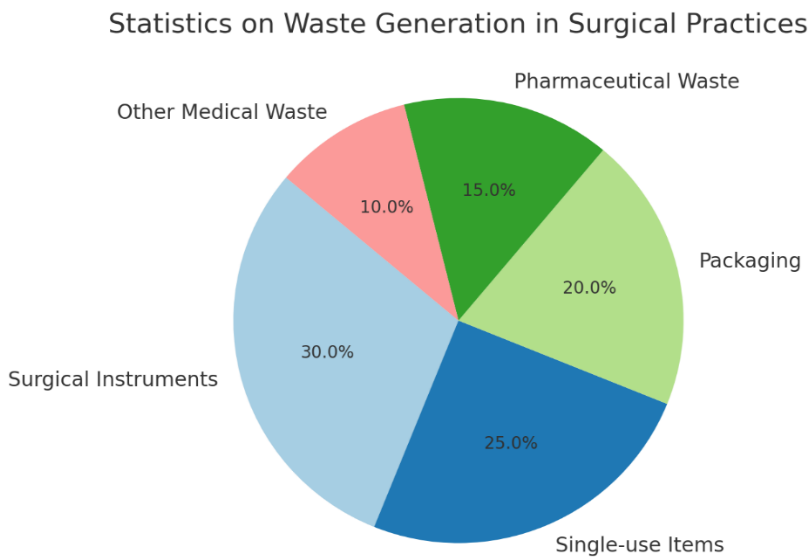

Figure 2. Pie chart illustrating the distribution of waste generation in surgical practices, broken down by categories such as surgical instruments, single-use items, packaging, pharmaceutical waste, and other medical waste (Binda et al., 2023; Richie, 2020; McNamee et al., 2022; Gordon, 2020).

Energy Consumption in Operating Rooms

Operating rooms (ORs) are among the most energy-intensive departments in a hospital. They require a regular and adequate supply of electricity to provide a clean, safe, and regulated environment for surgical procedures (McGain et al., 2019). The high energy requirements stem from maintaining ideal conditions, such as temperature control, air filtration, lighting, and the operation of important medical equipment (Mubarak, 2023).

ORs use energy from a variety of sources (Figure 3). Heating, ventilation, and air conditioning (HVAC) systems are the most serious offenders because they vary air quality, humidity, and temperature (Mubarak, 2023). These devices, which operate at total capacity around the clock, provide sterility and emergency preparedness even when the OR is not in use (Mubarak, 2023).

Aside from the many electronic instruments and tools used during operations, such as anaesthetic machines, monitoring, and sterilizing equipment, surgical lights—which often need high intensity—are a significant energy drain (Ali et al., 2023).

Along with high operating expenses, constant energy usage has an environmental impact on healthcare institutions (Ali et al., 2023). Low energy consumption in operating rooms, achieved via efficient methods and technology, is critical to reducing the environmental impact of surgical procedures and encouraging healthcare sustainability (Banhidy and Banhidy, 2022).

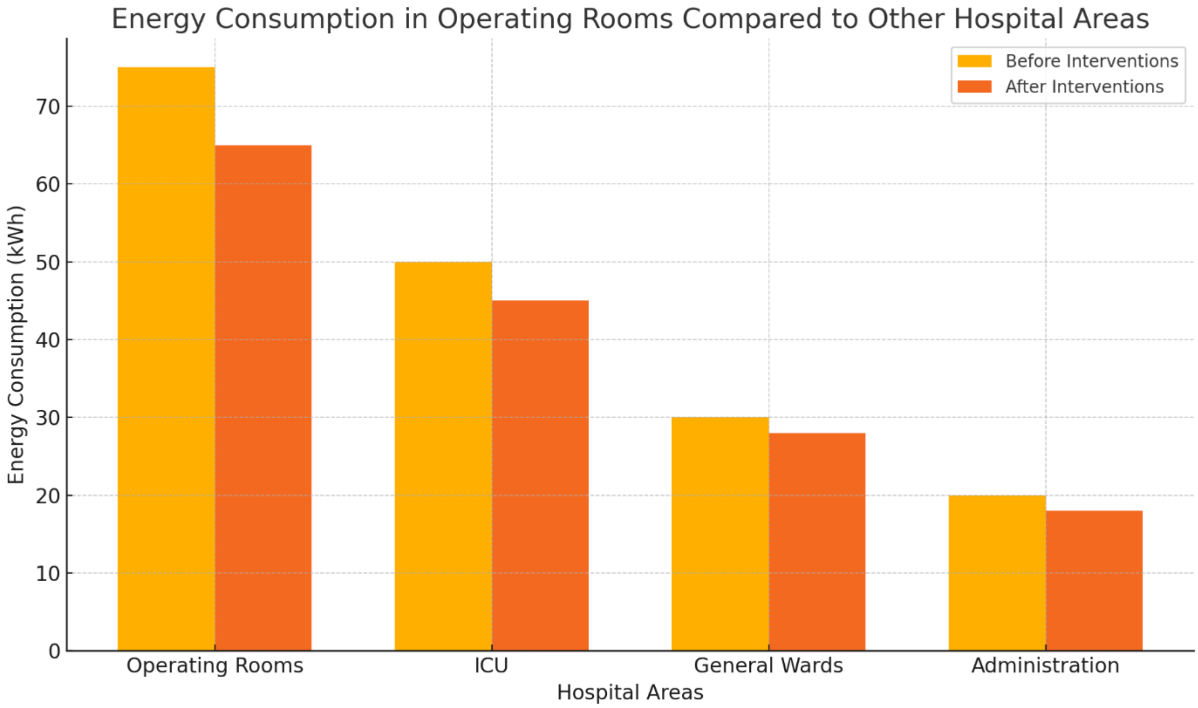

Figure 3. The bar chart that visualizes the energy consumption in different hospital areas, with a focus on operating rooms (Kwakye et al., 2010; Silva Filho et al., 2023; Gramlich et al., 2020; *Hussain* et al., 2018).

Water Usage in Surgical Practices

Water is an essential resource in healthcare, particularly in surgical procedures used for sterilization, cleaning, and maintaining aseptic conditions (Kwakye et al., 2011). The extensive water requirements for these operations add to the overall environmental impact of healthcare facilities (Crouch et al., 2022).

Sterilization and Sanitation Requirements

Sterilization is crucial in surgery to avoid infections and ensure patient safety. Sterilising surgical tools, linens, and other materials often entails using steam sterilizers, which need substantial volumes of water (Harris et al., 2021). Additionally, operating rooms must be carefully cleaned before and after each surgery, substantially increasing water use (Harris et al., 2021) (Figure 4).

This high demand for water is not only an environmental problem but also a difficulty in areas where water supplies are scarce or where hospitals seek to lessen their environmental impact (Engler et al., 2022). The widespread use of water in surgical settings also extends to preserving sterile environments. Handwashing, critical for avoiding illness transmission, is another area where water use is high. While critical for patient safety, these practices underline the need for more sustainable water management measures in healthcare (Sherman et al., 2020; Berniak-Woźny and Rataj, 2023).

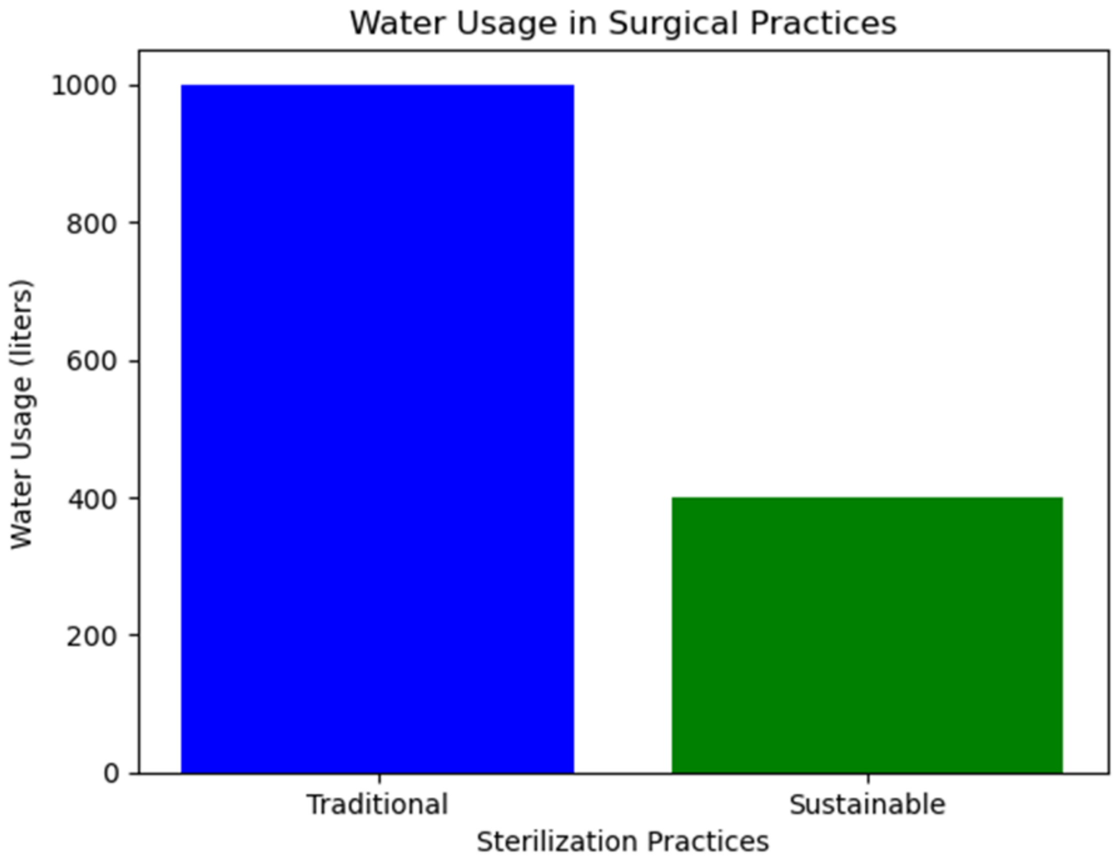

Figure 4. Water usage in surgical practices (Binda et al., 2023; Chaplin et al., 2020; Saver, 2011; McNamee et al., 2022).

Chemical and Anesthetic Emissions in Surgical Practices

Impact of Anesthetic Gases

Anaesthesia is routinely induced and maintained with anaesthetic gases such as nitrous oxide and halogenated medicines (e.g., isoflurane, desflurane, and sevoflurane) (Sherman et al., 2020; Berniak-Woźny and Rataj, 2023). Despite their high medicinal usefulness, these gases have serious environmental consequences. Many anaesthetic gases are potent greenhouse gases with a global warming potential (GWP) much greater than carbon dioxide (Berniak-Woźny and Rataj, 2023). Desflurane, for example, has a GWP that is almost 2,500 times that of carbon dioxide, indicating that its usage in surgery has a significant impact on climate change (Gerwig, 2014; Lam et al., 2023; Phoon et al., 2022) (Fig 5).

The fact that so many anaesthetic chemicals are discharged into the atmosphere during surgery exacerbates their environmental effect. Anaesthetic gases vary from other greenhouse gases because they are not collected or filtered before discharge, resulting in direct and uncontrolled contributions to global warming (Ho and Naseem, 2023). This underlines the need for alternate anaesthetic procedures or technology that may reduce environmental effects while maintaining patient safety (Nieuwenhuizen et al., 2023).

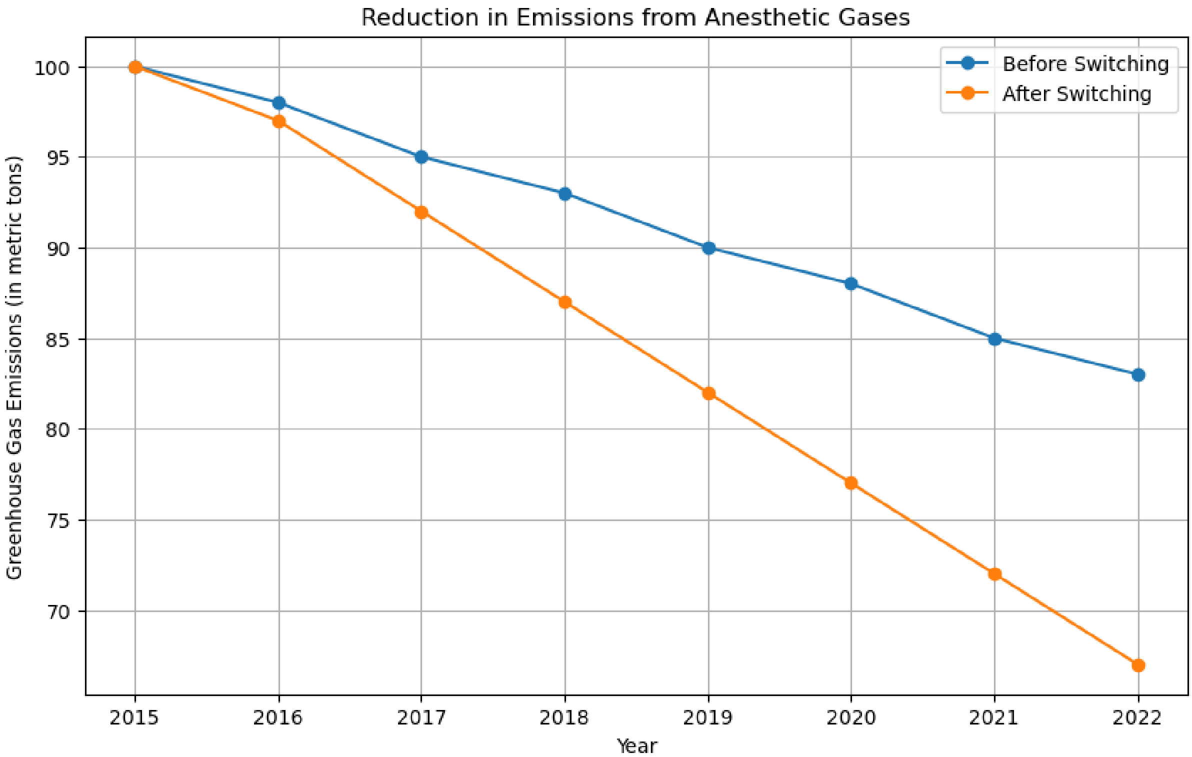

Figure 5. Line graph illustrating the impact of switching to environmentally friendly anaesthetics on greenhouse gas emissions over time (Tan, 2019; Gadi et al., 2023; Shum et al., 2022).

Disposal of Chemical Waste

Aside from anaesthesia emissions, another concern is how chemical waste from surgical procedures is disposed of. Many of the chemicals used in hospitals for sterilization, cleaning, and disinfection are broad-spectrum, damaging the environment and human health. Improper disposal of these chemicals may damage ecosystems and human health by polluting air, soil and water sources, among other concerns (Lee et al., 2023).

Chemical waste management in surgical settings necessitates strict adherence to environmental rules and optimal disposal procedures (Gramlich et al., 2020). Nonetheless, the large amount of this rubbish and its toxic nature make it a significant issue. To balance the environmental effects of surgical procedures, hospitals are urged to implement more sustainable practices, such as reducing toxic chemicals, improving waste separation, and investing in modern treatment technology (Nyholm et al., 2018; Smith et al., 2023).

Key Principles of Green Surgery

Green surgery is a therapeutic technique that aims to reduce the environmental impact of surgical operations while maintaining high levels of patient care (Blasco et al., 2023). By implementing sustainable practices, healthcare institutions may reduce waste, safeguard resources, and reduce carbon impact. Green surgery emphasizes waste reduction via the 3Rs (reduce, reuse, and recycle), increased energy efficiency, and sustainable resource utilization (Cunha, 2022; Hussain et al., 2018).

Reduce, Rese, Recycle (3Rs) in Surgical Settings.

Implementing the 3Rs—Reduce, Reuse, Recycle—in surgical settings is fundamental to minimizing waste and conserving resources (Binda et al., 2023; Gordon, 2020).

Reduce: Reducing the quantity of created trash is the first stage of the 3Rs. To achieve this goal, reducing single-use items, improving supply chain management to avoid overstocking, and using digital technologies to reduce paper waste may all be helpful. For example, electronic medical records (EMRs) remove the need for paper charts, while digital imaging reduces the need for actual film and associated chemicals (Gordon, 2020; Gorgun et al., 2023).

Reuse: Another critical feature of green surgery is reusing surgical tools and materials. Many surgical equipment, such as retractors and forceps, may be sanitized and reused, minimizing the need for disposable alternatives. Using appropriate sterilization processes on drapes, gowns, and other linens may also help to reduce waste. In addition to increasing the lives of resources and equipment, creative acts such as using medical gadgets for research or teaching (Gordon, 2020; Gorgun et al., 2023).

Recycle: Recycling is the last aspect of the 3Rs, including the proper segregation and disposal of recyclable resources. Operating rooms generate a large amount of waste, including plastic, paper, and packaging goods containing plastic. Starting recycling initiatives in surgical departments may assist in diverting a significant fraction of this garbage from landfills. For example, several hospitals have adopted the effective use of recycling blue wrap to keep surgical equipment clean, which significantly lowers waste. Recycling programs may also involve properly disposing and recycling electronic waste, such as old medical equipment (Gordon, 2020; Yates et al., 2021).

Case Studies and Successful Implementations

Many medical institutes have successfully used the 3Rs in surgical settings. For example, Kaiser Permanente, a prominent American healthcare provider, has incorporated sustainable practices into many aspects of its operations, including reusable surgical kits to reduce waste in operating rooms. Another example is the University of Vermont Medical Center, which has diverted over 40% of its garbage from landfills via a robust recycling program, therefore reducing significant waste (Goettke et al., 2021; McGain et al., 2019; Banhidy and Banhidy, 2022).

Energy Efficiency in Surgical Settings

Operating rooms are among the most energy-intensive spaces in hospitals, using large quantities of power for ventilation, lighting, and equipment. Using energy-efficient approaches is critical for reducing the environmental impact of surgical procedures (Kwakye et al., 2011).

Strategies for Reducing Energy Consumption: One sensible way is to utilize energy-efficient lighting, such as LED lights, which consume less power and last longer than standard lighting. Improving HVAC (heating, ventilation, and air conditioning) systems is another option to save energy while still meeting air quality regulations. This procedure may include the use of energy recovery ventilators (ERVs), which collect and reuse energy from exhaust air (Crouch et al., 2022; Harris et al., 2021).

Examples of Energy-Efficient Technologies

Computerized energy management systems and energy-efficient surgical equipment may further reduce energy use. For example, surgical robots and energy-efficient anesthetic equipment could reduce power consumption. Furthermore, installing motion sensors in running rooms to manage ventilation and lighting when they are not in use would significantly reduce energy consumption (Harris et al., 2021; Gerwig, 2014; Hussain et al., 2018).

Sustainable Procurement

Sustainable procurement involves choosing items and services that have a minimal environmental effect throughout their life cycle, from manufacture to disposal (Tan, 2019).

Criteria for Selecting Sustainable Products: When purchasing surgical equipment, hospitals should go for reusable, sustainable, and low-packaging options. Furthermore, suppliers' environmental policies and practices should be considered to ensure the whole supply chain meets sustainability requirements (Anastasopoulos and Papalois, 2022).

Impact of Procurement Choices on Sustainability: Procurement decisions have a wide-ranging impact on sustainability. Choosing suppliers that utilize renewable energy in their production processes or provide take-back programs for obsolete equipment, for example, lowers the total carbon footprint of surgical procedures (Anastasopoulos and Papalois, 2022). Choosing durable and reusable items also helps to decrease waste by reducing the frequency of purchases, hence conserving resources (Rahat., 2023).

Overall, the fundamental concepts of green surgery—reduce, reuse, recycle, energy efficiency, and sustainable procurement—play an important role in reducing the environmental effect of surgical activities (Jedrzejko et al., 2021). Healthcare institutions may contribute to building a more sustainable future by incorporating these concepts into their everyday operations, ensuring the delivery of high-quality patient care (Gadi et al., 2023).

Practical Strategies for Implementing Green Surgery

While maintaining excellent patient care standards, green surgery seeks to reduce the environmental effects of surgical procedures. Acceptable methods for green surgery include waste management, energy efficiency, water use, and emissions reduction (Mubarak, 2023) (Figure 6).

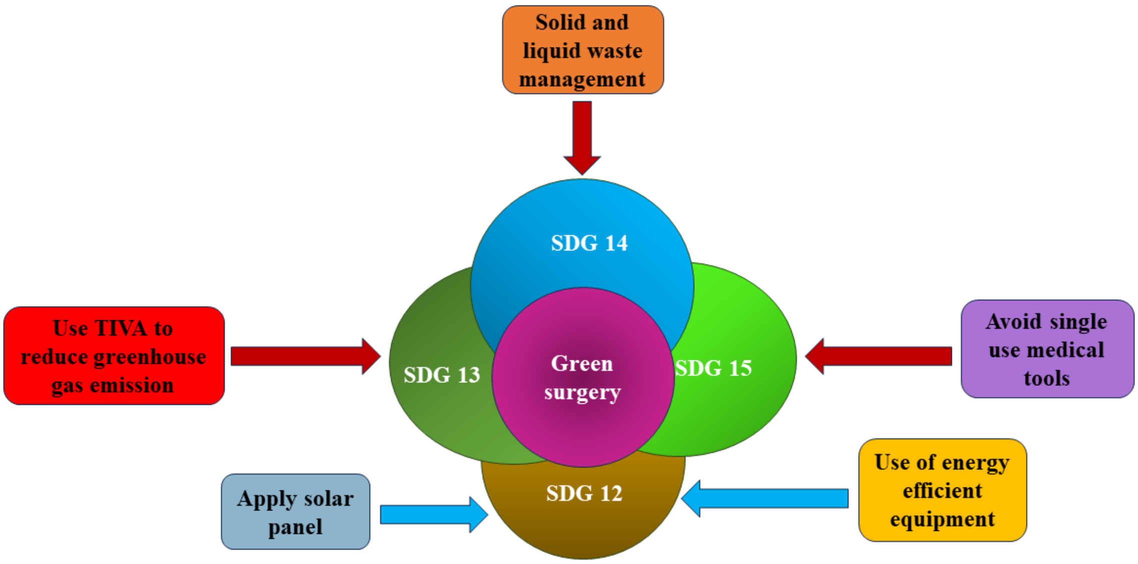

Figure 6. Several strategies can help implement green surgery and achieve specific Sustainable Development Goals (SDGs).

Effective waste management, reducing the use of disposable medical tools, and minimizing the use of traditional greenhouse gas-emitting anaesthetics can directly contribute to a healthier climate and stabilising aquatic and terrestrial ecosystems. These actions are crucial for maintaining biodiversity, aligning with SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land), as indicated by the brown arrow. Additionally, using non-conventional energy sources, such as solar power and energy-efficient equipment, supports the achievement of SDG 12 (Responsible Consumption and Production).

Waste Management

Proper waste management is a crucial part of green surgical practices. Surgical settings generate substantial trash, most of which may be avoided or repurposed (Mubarak, 2023; Ali et al., 2023; Saha, 2023).

Effective Recycling Programs: Hospitals may have extensive recycling systems to separate and properly dispose of recyclable items such as plastic, metals, and paper products. Encouragement of staff trash separation and the placement of clearly designated containers in strategic places may enhance recycling efforts (Banhidy and Banhidy, 2022).

Minimizing Single-Use Items: The dependence on single-use items in surgery significantly increases waste creation. Surgical teams should use reused instruments and materials whenever feasible to decrease waste. Using reusable surgical gowns, drapes, and equipment, for example, may significantly reduce throwaway waste and, over time, assist in reducing environmental impact and expense (Kwakye et al., 2011).

Energy Conservation

Operating rooms are high-energy structures requiring extensive ventilation, air conditioning, heating, and lighting. Energy-saving techniques are required to make operations more sustainable (Crouch et al., 2022).

Optimizing Operating Room Energy Use: Small modifications to thermostat settings, shutting off unnecessary appliances, and utilizing energy-efficient lighting may result in considerable energy savings. Modern HVAC systems that adjust airflow depending on occupancy may help to cut energy consumption without jeopardizing patient safety (Harris et al., 2021).

Incorporating Renewable Energy Sources: Hospitals may consider using solar or wind power as renewable energy sources to supply the electricity required for surgical operations. Healthcare facilities may lower their carbon footprint and contribute to larger environmental objectives by producing some of their energy from renewable sources (Harris et al., 2021).

Water Conservation

Water is necessary for surgery, utilized chiefly for sanitation and sterilization reasons. Still, water use might be reduced to lessen environmental effects (Engler et al., 2022).

Techniques for Reducing Water Usage: Installing low-flow faucets, automated scrub stations, and water-saving sterilizers in surgical settings can significantly reduce water consumption. Teaching employees water-saving measures and measuring water use regularly might help to improve these efforts even further (Berniak-Woźny and Rataj, 2023).

Sustainable Sterilization Practices: Sanitizing surgical equipment is critical, even if it requires much water. Using water-saving technology (closed-loop systems that recycle water throughout the sterilization process) may help minimize water use. Other sterilizing procedures, such as UV sterilization or dry steam, may also help minimize water use while ensuring that equipment is thoroughly cleaned (Gerwig, 2014; Lam et al., 2023).

Reducing Emissions

Surgical operations, mainly using anesthetic gases and other energy-intensive activities, may contribute to greenhouse gas emissions. Making surgery more sustainable requires reducing these pollutants (Lee et al., 2023).

Using Environmentally Friendly Anesthetics: Traditional anaesthetic medicines such as nitrous oxide and desflurane emit significant amounts of greenhouse gases. Changing to lower-effect options, such as total intravenous anaesthesia (TIVA) or sevoflurane, would significantly minimize the environmental impact of anaesthesia. In addition, gas collection and recycling technologies might help to reduce emissions (Ho and Naseem, 2023; Nieuwenhuizen et al., 2023).

Reducing the Carbon Footprint of Surgeries: Aside from anaesthetics, low-emission mobility alternatives for personnel and patients may assist in lowering the overall carbon footprint of operations by optimizing surgical schedules to limit energy use, and local sourcing of materials and supplies reduces transportation-related emissions (Lee et al., 2023).

Green surgery requires a comprehensive strategy that addresses emissions, waste, energy, water, and materials (Lee et al., 2023). These practical solutions may assist healthcare institutions in significantly reducing their environmental footprint while offering excellent surgical care. These innovations pave the way for more environmentally friendly surgical procedures as the healthcare sector recognizes the importance of sustainability (Blasco et al., 2023; Hussain et al., 2018).

Challenges and Barriers to Implementing Green Surgery

Although ecologically sustainable, the transition to green surgery confronts several problems and limitations. All of these issues—institutional obstacles, financial concerns, legislative and legal challenges—must be addressed to allow more significant widespread usage (Tan, 2019; Anastasopoulos and Papalois, 2022).

Institutional Resistance

One of the most significant barriers to adopting green surgery is institutional reluctance. This opposition is often the consequence of substantial inertia inside healthcare organizations, where traditional procedures are deeply embedded, and changes—particularly those involving new methods or technology—are frequently regarded with mistrust (Rahat et al., 2023). Overcoming this hurdle requires a multifaceted approach:

Overcoming Inertia and Resistance to Change: Concerns about the potential effect on patient care, workflow interruptions, or the perceived complexity of integrating new systems may make healthcare professionals and management hesitant to use green surgical procedures. Education and training that emphasizes the environmental, ethical, and long-term financial advantages of green surgery may assist in overcoming this resistance (Jedrzejko et al., 2021). Success stories from other firms implementing sustainable practices might be pretty inspirational (Gadi et al., 2023).

Strategies for Gaining Institutional Support: Obtaining institutional support for green surgery requires a compelling case for sustainability. This may be done by merging green surgical aims with broader institutional principles and goals, such as improving patient outcomes and minimizing operating costs (Gadi et al., 2023). Key participants in the planning and execution process, such as surgeons, anesthetists, nurses, and administrators, should be included. Having multidisciplinary committees to supervise environmental efforts encourages responsibility and collaboration (Gadi et al., 2023).

Cost Considerations

Money is an important component in healthcare corporations' decision-making; therefore, the idea that green surgery is more costly than traditional approaches may present a substantial problem (Jedrzejko et al., 2021). However, considering the long-term financial advantages of sustainability, this image may not necessarily reflect reality (Gadi et al., 2023).

Balancing Sustainability with Cost-Effectiveness: Green surgical procedures may need initial expenditures in training, equipment, and new technologies. Long-term benefits from resource conservation, waste management modifications, and reduced energy use may help to offset these expenses (Gadi et al., 2023; Shum et al., 2022). Green surgery, for example, is both environmentally and financially viable because reused surgical instruments and energy-efficient technology may ultimately lower operating costs (Urquhart et al., 2020).

Long-Term Financial Benefits of Green Surgery:

Beyond immediate cost savings, green surgery may provide long-term financial benefits by strengthening the institution's image, recruiting environmentally conscientious patients, and lowering legal risks associated with environmental noncompliance (Lee et al., 2023; Tan, 2019). Companies that implement green practices may also be eligible for subsidies, incentives, or tax breaks, enhancing the financial feasibility of sustainable efforts (Engler et al., 2022). Fig 7 shows the cost analysis of green surgery.

Regulatory and Policy Issues

Navigating the complex labyrinth of rules and regulations governing green surgery is yet another challenge. While some regulations promote sustainability, others make it harder to implement green policies (Mubarak, 2023).

Navigating Regulations and Policies:

Medical facilities must follow local, national, and international norms that govern surgical practices, waste disposal, and environmental effects (Mubarak, 2023). Under some scenarios, current legislation may not adequately support or permit green surgical practices, limiting their adoption (Mubarak, 2023). To navigate these obstacles, institutions must be aware of current legislation and collaborate with legal and policy specialists to ensure compliance while achieving long-term objectives (Ali et al., 2023).

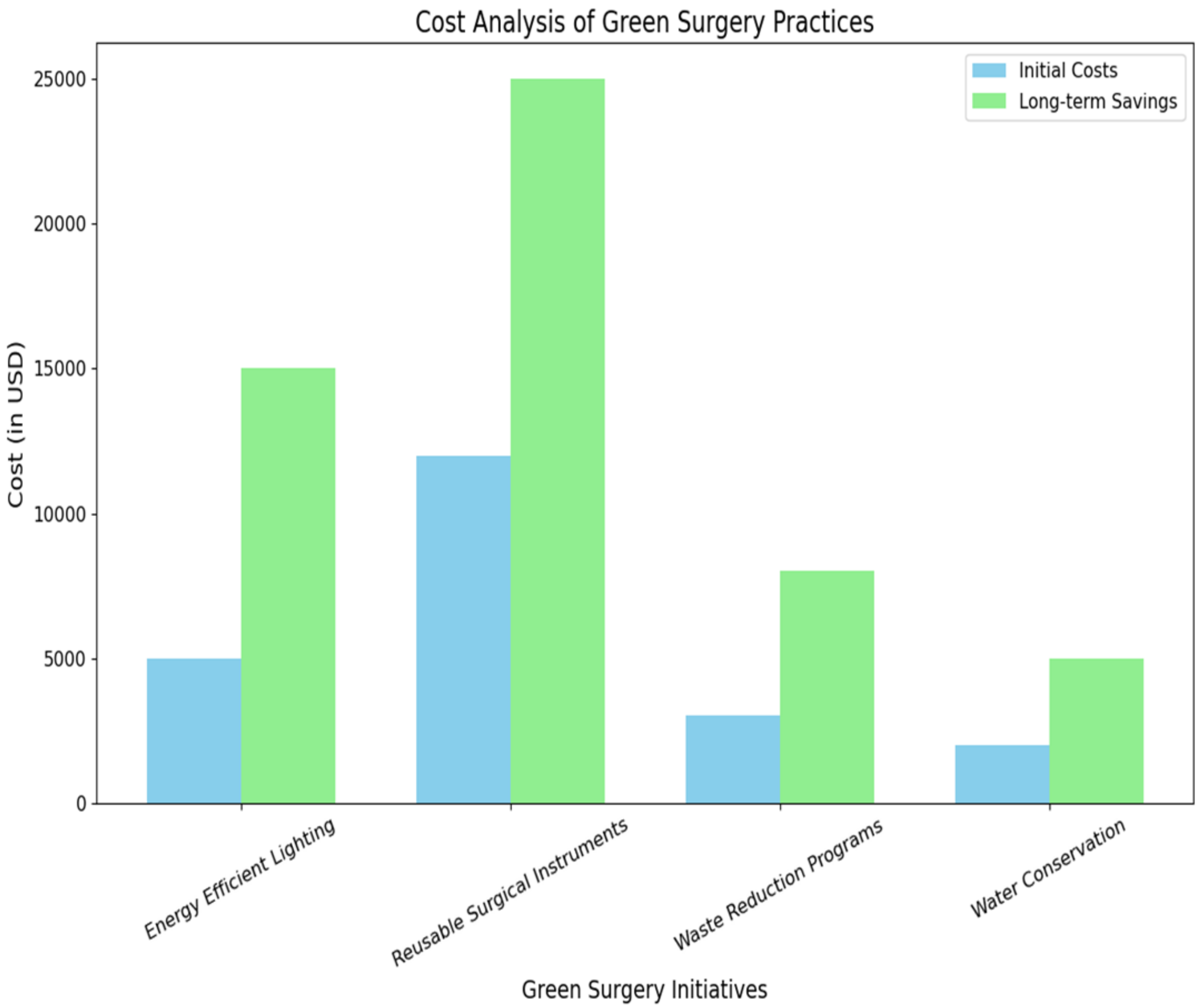

Figure 7. Cost Analysis of Green Surgery Practices (Wu and Cerceo, 2021; Lee and Lee, 2022; Aboueid et al., 2023; Vacharathit et al., 2021).

Advocating for Supportive Policies:

Fighting for legislation that promotes green surgery may help you overcome legislative and legal barriers. Working with environmental advocacy organizations, political authorities, and professional associations might help campaign for legislative improvements that promote sustainable healthcare practices (Rahat et al., 2023). Institutions can help influence future regulations by participating in trial programs, collecting data on the environmental effects of surgical procedures, and demonstrating the practicality and advantages of green surgery (Jedrzejko et al., 2021).

There are several obstacles to green surgery, but they are manageable (Gadi et al., 2023). Healthcare organizations may progress toward a more sustainable future by overcoming institutional opposition, thoroughly scrutinizing costs, and addressing regulatory issues (Gadi et al., 2023). The transition to green surgery is not only a moral imperative, but it is also feasible and financially sound, and it will benefit both the world and patients in the long run (Shum et al., 2022).

Case Studies and Success Stories in Green Surgery

With creative hospitals and organizations leading the way in integrating sustainable practices that help the environment and enhance patient care, the movement for green surgery has made tremendous progress (McGain et al., 2019). This section discusses the characteristics of these premier hospitals, their innovative technology and procedures, and the results of their green surgery initiatives.

Pioneering Hospitals and Institutions

Many hospitals and businesses worldwide have set an example for others by pioneering green surgical procedures. While maintaining or increasing the quality of care they deliver, these institutions have taken substantial steps to reduce their environmental impact (Lee et al., 2023).

Profiles of Hospitals Leading in Green Surgery

Cleveland Clinic, USA: Cleveland Clinic is well-known for its commitment to environmental sustainability in medicine. The clinic has implemented several sustainability efforts, including sustainable procurement practices, waste reduction programs, and energy-efficient operating rooms. They have also worked to reduce their surgical operations' carbon footprint by utilizing environmentally friendly anaesthetics and improving energy efficiency in their facilities (Kwakye et al., 2010; Silva Filho et al., 2023; Harris et al., 2017).

University Hospitals of Leicester NHS Trust, UK: One of the first NHS Trusts to incorporate sustainability into surgical operations, the Trust's efforts to reduce single-use goods in operations, promote the use of reusable gadgets, and implement energy-saving policies in operating theatres demonstrate its commitment to reducing its environmental impact. The Trust has also been attempting to foster an environmentally responsible culture by educating its employees on the importance of sustainability (Binda et al., 2023; Silva Filho et al., 2023; McNamee et al., 2022).

Karolinska University Hospital, Sweden: The leading green healthcare center in Europe, Karolinska University Hospital, has the hospital has developed a comprehensive sustainability plan, focusing on energy efficiency, waste reduction, and the use of green technology. Karolinska's surgical teams have been particularly effective in introducing green surgery techniques, such as careful disposal of surgical waste to reduce environmental impact and the use of energy-efficient lighting and ventilation systems in operating rooms (Yates et al., 2021; McGain et al., 2019; Ali et al., 2023). Figure 8 shows the growth in adaptation rates of green surgery practice and table 1 has shown the key outcomes from top hospitals and innovative technologies.

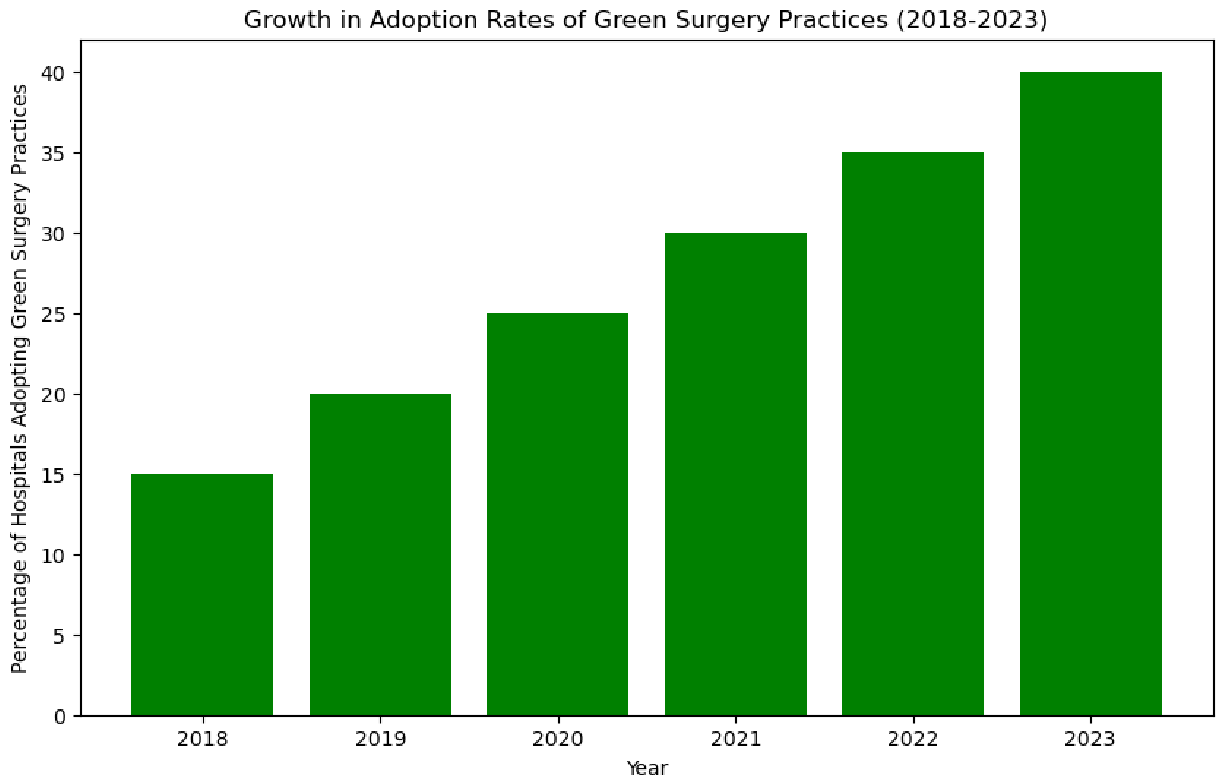

Figure 8. Growth in Adoption Rates of Green Surgery Practices (2018-2023) (Mostepaniuk et al., 2023; Crouch et al., 2022; Harris et al., 2021; Nyholm et al., 2018).

Table 1: Key Outcomes from Pioneering Hospitals and Innovative Technologies (Ali and Wernham, 2022; Ma and Han, 2022; Yun et al., 2023).

Hospital/Technology	Key Outcomes	Improvements
Mayo Clinic	Waste Reduction	Reduced medical waste by 30% through recycling programs
Cleveland Clinic	Energy Savings	Achieved 20% energy savings by implementing LED lighting and energy-efficient HVAC systems
Advanced Water Recycling Systems	Water Conservation	Saved 15 million gallons of water annually with advanced water recycling systems
Johns Hopkins Hospital	Waste Reduction	Decreased hazardous waste by 25% using safer disposal methods
Smart Grid Technology	Energy Savings	Lowered energy consumption by 18% with smart grid technology
Kaiser Permanente	Water Conservation	Reduced water usage by 40% through low-flow fixtures and rainwater harvesting
Karolinska Institute	Energy Savings	Implemented solar panels and energy-efficient systems, reducing energy consumption by 22%

Specific Initiatives and Their Outcomes

Waste Reduction at Cleveland Clinic: The Cleveland Clinic's waste-reduction initiatives have significantly reduced medical waste created during surgery. By using reusable surgical instruments and limiting disposable materials, the clinic reduces the amount of waste that ends up in landfills. Their environmental impact has also been significantly reduced by their attempts to recycle materials like surgical drapes and gowns (Kwakye et al., 2010; Silva Filho et al., 2023; Harris et al., 2017).

Energy Efficiency at University Hospitals of Leicester NHS Trust: The Trust's emphasis on energy efficiency has yielded noteworthy achievements. Their operating theatres now include HVAC systems and energy-efficient lighting, which has helped to reduce energy use by more than 20%. They are lowering the hospital's carbon footprint, resulting in considerable financial savings that may be reinvested in patient care (Binda et al., 2023; Silva Filho et al., 2023; McNamee et al., 2022).

Green Anesthesia at Karolinska University Hospital: Karolinska's use of ecologically friendly anaesthetic gases has changed hospital greenhouse gas reduction efforts. The hospital utilises more sustainable alternatives instead of typical anaesthetic gases that emit significant greenhouse gases. While preserving high-quality patient care, this technique has dramatically decreased the hospital's impact on climate change (Yates et al., 2021; McGain et al., 2019; Ali et al., 2023).

Innovative Technologies and Approaches

Introducing new technology and procedures has boosted the popularity of green surgery. These technologies enhance patient outcomes, increase efficiency, and make procedures more sustainable (Banhidy and Banhidy, 2022).

Breakthrough Technologies in Sustainable Surgery

Energy-Efficient Operating Rooms: Hospitals such as Cleveland Clinic and Karolinska University Hospital have invested in energy-efficient operating rooms outfitted with contemporary lighting, HVAC, and surgical equipment. These modifications cut carbon emissions and energy usage while maintaining treatment quality. LED surgical lights, for example, generate less heat and utilize far less energy than traditional halogen lights, eliminating the need for air conditioning (Kwakye et al., 2010; Silva Filho et al., 2023; Harris et al., 2017).

Green Sterilization Techniques: Traditional sterilization processes often require enormous amounts of water and power. However, forward-thinking institutions use novel sterilization procedures, such as low-temperature hydrogen peroxide sterilization and ozone-based systems. Aside from being energy efficient, these technologies employ fewer chemicals, reducing the environmental effect of surgical sterilization processes (Richie, 2020; Saver, 2011; McNamee et al., 2022).

Telemedicine and Remote Surgery: The COVID-19 outbreak has accelerated the adoption of telemedicine and remote surgery, which may assist in lessening the environmental effects of medicine. Telemedicine and remote surgery may help minimize the carbon footprint of medical treatment by reducing the need for staff and patient travel (Tan, 2019; Anastasopoulos and Papalois, 2022). Remote surgery using robotic equipment reduces treatment waste and may enhance accuracy and results (Rahat et al., 2023).

Examples of Innovative Surgical Practices

Minimally Invasive Surgery (MIS): Green surgery primarily relies on minimally invasive surgery because it uses fewer resources and produces less waste than conventional open surgery (Jedrzejko et al., 2021). Smaller incisions used in MIS procedures, such as laparoscopy and robotic-assisted surgery, serve to minimize the need for surgical supplies by shortening hospital stays. This reduces waste and surgical therapy's overall environmental impact (Gadi et al., 2023).

Reusable Surgical Instruments: One simple but efficient technique to reduce operating room waste is to move from disposable to reusable surgical equipment (Binda et al., 2023). For example, organizations such as the University of Leicester NHS Trust have often made washing, disinfecting, and reusing surgical equipment feasible, lowering the need for single-use supplies significantly (Silva Filho et al., 2023). This technique reduces waste and lowers the cost of purchasing trash devices (McNamee et al., 2022).

Green Anesthesia Practices: According to Karolinska University Hospital, sustainable surgery heavily relies on green anaesthesia procedures (Shum et al., 2022). Aside from employing environmentally friendly anaesthetic gases, numerous hospitals are looking into the use of regional anaesthesia treatments, such as nerve blocks, which reduce the need for general anaesthesia and its associated environmental effects (Shum et al., 2022). These methods reduce the adverse effects of anaesthesia, hence facilitating patient recovery.

Sustainable Procurement: Sustainable procurement is the purchase of surgical instruments and equipment with a lower environmental effect during its lifespan. Cleveland Clinic, for example, has created a sustainable procurement strategy that emphasizes products manufactured from recyclable materials, equipment with energy-efficient certifications, and suppliers dedicated to environmentally friendly operations (Urquhart et al., 2020; Ament et al., 2012). From manufacture to disposal, this method guarantees that sustainability is addressed at all stages of the surgical supply chain (Ament et al., 2012; Mousa and Othman, 2020; Wu and Cerceo, 2021).

Case studies and success stories from creative organizations and hospitals demonstrate the transformative potential of green surgery (Lee and Lee, 2022; Aboueid et al., 2023). These institutions have demonstrated that it is possible to provide high-quality surgical treatment while significantly reducing environmental impact through innovative technology and procedures (Vacharathit et al., 2021; Migdadi and Omari, 2019). Others may replicate the unique efforts performed by institutions such as Karolinska University Hospital, University of Leicester NHS Trust, and Cleveland Clinic (Ali and Wernham, 2022; Ma and Han, 2022; Yun et al., 2023).

These successful stories highlight the importance of institutional devotion, multidisciplinary collaboration, and continual education in achieving healthcare sustainability (Rashid et al., 2024; Mohamed and Ibrahim, 2024; Mago et al., 2024).

Although problems persist, the path to green surgery is long-term, and the results provide a roadmap for the future. More hospitals using sustainable practices will have a significant, combined effect on global health and the environment, paving the way for a more resilient and sustainable healthcare system.

Conclusion

Green surgery is a significant advancement in contemporary medicine that stresses the need to decrease environmental impact without sacrificing patient care. Cleveland Clinic, University Hospitals of Leicester NHS Trust, and Karolinska University Hospital's unique programs demonstrate the significant advantages of long-term surgical methods. From green anaesthetic procedures to energy-efficient operating rooms, these institutions have developed various initiatives to reduce waste, protect resources, and lower carbon emissions.

Aside from environmental sustainability, green surgery provides significant cost savings and better patient outcomes. Hospitals can reduce operating costs by implementing sustainable procurement practices, energy-efficient technologies, and the 3Rs (reduce, reuse, recycle), contributing to a better society. New surgical procedures, such as minimally invasive surgery and reused tools, also help reduce surgery's total environmental impact. One cannot overstate the ethical importance of sustainability in the healthcare system. Healthcare practitioners must preserve public health and ensure their activities do not affect the environment or future generations. The success stories from well-known hospitals demonstrate that sustainability is not only achievable but also critical to the long-term viability of healthcare systems.

The future of healthcare rests on inspiring a widespread shift toward ecologically friendly surgical practices. Collaboration across all healthcare facilities, exchanging best practices, technology, and resources, will contribute to the widespread adoption of green surgery. It also necessitates a culture shift in which sustainability precedes healthcare decision-making, from procurement to patient care.

To summarize, green surgery is an essential transformation in healthcare, not only a fad. Hospitals and surgical teams can significantly contribute to environmental preservation by implementing sustainable practices while improving patient care. The achievements of trailblazer institutions provide a clear path for others to follow, ensuring that surgery's future is not just inventive but sustainable. As the trend toward green surgery gains traction, it promises to create a healthcare system that is both ecologically responsible and morally sound, helping patients, healthcare professionals, and the earth in the present and future.

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Chapter- 12

Indian Medicinal Plants and its Importance to Explore World Wide Mass Education through Integrated Media Learning Process: A Challengeable Envisage at Present Era

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Keywords: Education, Globalization, Learning, Medicinal, Plant, Teaching, Teacher

Abstract:

Experimentation coincides with the teaching-learning process. According to learning strategies is to be used. The teachers are deplorable in two types of media orientation: teacher–centered strategies and student–centered strategies. The selection of this strategy is closely related to integrating technology and media in a learning process. Specifically, this integration becomes the presentation of a concept by displaying a video of a story or showing how to conjure it up. The student-centred strategy is an activity that involves students in active learning, in which the teacher's position is more of the facilitator, who will ensure that learning objectives will be achieved. Integrating technology and media in a learning process will provide convenience and benefits not only to the teachers but also to the students. Medicinal plants, their importance, and globalization are enhanced through the teaching-learning process that ensures livelihood sustenance among the people at large. Growing plants around the house have multi-dimensional benefits as they have enormous potential in preventing and treating various ailments. Apart from this, plants provide essential nutritional requirements through food ingredients. The chosen medicinal plants also keep the environment clean by improving the air quality. The developing plants help preserve Indigenous knowledge, culture, and its potentiality on a worldwide consideration, which can empower women's endeavors, community enhancement, and knowledge propagation to cure various ailments; medicinal uses of the plants encourage challengeable ensue in the 21st century. The present sequel has accentuated the ten most important medicinal plants that grew in India and are accessible in various parts of the sovereign state. The selected top ten medicinal plants are Aloe vera (*Aloe barbadensis*), Brahmi (*Bacopamonnieri*), Holy basil (Ocimumtenuiflorum), Neem (*Azadirachtaindica*), Peppermint (*Menthapiperita*), Turmeric (*Curcuma longa*), Amla (Phyllanthusemblica), Guggul (Co*mmiforawhgitii*), Shatavari (*Asparagus racemosus*) and Ashwagandha (*Withaniasomnifera*). Integration of these ten medicinal plants, their uses, and importance in humane society through media learning is a challengeable educational enhancement at this present juncture, the 21st century, encouraging global accumulation and educational upliftment for societal benefit worldwide.

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Introduction:

Indian medicinal plants hold significant importance due to their rich diversity and traditional medicinal properties (Acharya et al., 2010; Basu et al., 2009; Basu et al., 2019; Basu and Cetzal-Ix, 2018). They have been integral to Ayurveda, the ancient Indian system of medicine, for centuries (Basu, 2017; Basu, 2018; Martínez-Puc et al., 2018; Sarkar et al., 2021; Ghosh et al., 2022; Acharya et al., 2022a&b, 2023; Sarkar et al., 2024). These plants contribute to:

Cultural Heritage: Medicinal plants are deeply rooted in India's cultural and traditional practices, shaping the heritage of Ayurveda and other indigenous medicinal systems.

Healthcare: Many plants have proven therapeutic value, providing natural remedies for various ailments. They offer alternatives or complements to modern medicine, contributing to holistic healthcare. Biodiversity: India is home to many medicinal plant species, contributing to global biodiversity. Conserving these plants is essential for maintaining ecological balance and preserving genetic resources. Economic Value: Medicinal plants play a crucial role in the economy, providing livelihoods for communities involved in cultivation, harvesting, and processing. They are a source of income for many. Drug Discovery: Active compounds from these plants have been used to develop pharmaceutical drugs. Traditional knowledge about these plants is a valuable resource for modern drug discovery.

Sustainable Agriculture: Many medicinal plants are cultivated using traditional agricultural practices, which promote sustainable farming methods and contribute to soil health.

Environmental Conservation: The conservation of medicinal plants often involves protecting natural habitats. This conservation effort contributes to overall environmental preservation.

Global Health: As interest in natural and traditional medicine grows globally, Indian medicinal plants have the potential to benefit people worldwide, fostering international collaborations in research and healthcare. The importance of Indian medicinal plants extends beyond healthcare to encompass cultural, economic, environmental, and global dimensions.

Need for education and awareness regarding Indian medicinal plants.

Education and awareness regarding Indian medicinal plants (Acharya et al., 2010; Basu, 2018a, b; Basu et al., 2009; 2019; Basu and Cetzal-Ix, 2018) are crucial for several reasons:

Preservation of Traditional Knowledge: Many valuable insights about the use of medicinal plants are embedded in traditional practices. Education helps document and preserve this knowledge, preventing its loss over time without proper documentation and due to the absence of proper teaching methods and the availability of qualified teachers.

Promotion of Sustainable Practices: Understanding medicinal plant cultivation, harvesting, and processing is essential for sustainable practices. Education can encourage responsible harvesting and cultivation methods to ensure the long-term availability of these plants.

Holistic Healthcare: Awareness promotes the integration of traditional and modern medicine, fostering a holistic approach to healthcare. This can lead to more comprehensive and personalized treatment options. Cultural Heritage: Education helps people appreciate the cultural significance of medicinal plants, connecting them to their heritage and fostering a sense of pride and responsibility for preserving traditional practices. Economic Empowerment: Knowledge about medicinal plants empowers communities economically. Education can help them leverage these plants' economic potential, whether through sustainable harvesting or value-added products.

Conservation of Biodiversity: Awareness about the importance of medicinal plants contributes to efforts to conserve biodiversity through globalization. People become more conscious of the need to protect natural habitats that support these plants.

Drug Discovery and Research: Education fosters interest in the scientific study of medicinal plants, potentially leading to new discoveries and innovations in pharmaceuticals. This research can benefit both traditional medicine and modern drug development.

Community Health and Well-being: Knowledge about medicinal plants at the community level enhances self-reliance in healthcare. Communities can address common health issues using locally available resources.

Environmental Conservation: Education can raise awareness about the environmental impact of overharvesting and unsustainable practices. This understanding encourages responsible behaviour and conservation efforts.

Global Collaboration: Increased awareness facilitates collaboration between traditional healers, scientists, and healthcare professionals on a global scale. This exchange of knowledge can lead to advancements in healthcare and biodiversity conservation.

In summary, education and awareness play a pivotal role in preserving traditional knowledge, promoting sustainable practices, and leveraging the benefits of Indian medicinal plants for the well-being of individuals, communities, and the environment.

Integrated Media Learning Process for some selected Indian medicinal plants

An Integrated Media Learning Process for some selected Indian Medicinal Plants such as Aloe vera (*Aloe barbadensis*), Brahmi (*Bacopamonnieri*), Holy basil (Ocimumtenuiflorum), Neem (*Azadirachtaindica*), Peppermint (*Menthapiperita*), Turmeric (*Curcuma longa*), Amla(Phyllanthusemblica), Guggul (Co*mmiforawhgitii*), Shatavari (*Asparagus racemosus*) and Ashwagandha (*Withaniasomnifera*) could involve a multifaceted approach to cater to different learning styles and preferences(Acharya *et al*, 2010; Basu *et al*., 2009; 2019; Basu & Cetzal-Ix, 2018). Here is a suggested framework:

Online Platforms:

Webinars and Lectures: Experts will conduct online lectures covering the historical, cultural, and scientific aspects of Indian medicinal plants.

Interactive Websites: Develop interactive websites with modules for plant identification, cultivation methods, and medicinal uses.

Visual Media:

Documentaries and Videos: Create documentaries showcasing the journey of medicinal plants from cultivation to usage, emphasizing their cultural significance.

Virtual Tours: Provide virtual tours of medicinal plant gardens, showcasing diverse species and their applications.

Mobile Applications:

Plant Identification Apps: Develop apps that use image recognition to identify medicinal plants and provide details on their uses and cultivation.

Educational Games: Create interactive games to learn about medicinal plants, making the process engaging and informative.

Social Media Campaigns:

Awareness Campaigns: Run social media campaigns to share bite-sized information, infographics, and success stories about Indian medicinal plants.

Live Sessions: Conduct live Q&A sessions with experts on platforms like Instagram or Facebook.

Print and Publications: Booklets and Brochures: Distribute printed materials providing essential information on common medicinal plants, their uses, and cultivation tips.

Magazine Features: Collaborate with magazines to publish articles on the importance and conservation of medicinal plants.

Workshops and Training Programs: Organize workshops for hands-on experience identifying, cultivating, and processing medicinal plants.

Training Programs: Offer training programs for farmers, healthcare professionals, and enthusiasts interested in medicinal plant cultivation.

Collaboration with Educational Institutions: This will credibly help in building a network among learners and trainers in building a long-term sustainable platform for gathering and expanding knowledge on various Indian medicinal plants, their uses and applications in treating various diseases and their commercial production, as well as conservation strategies on a comprehensive manner. Such collaboration, cooperation, coordination and communication (4Cs) can build a strong tradition of passing knowledge and Training in dealing with various aspects of Indian medicinal plants, as discussed above.

Curriculum Integration: Work with schools and colleges to integrate modules on Indian medicinal plants into their curricula.

Research Collaborations: Foster collaborations between educational institutions and traditional healers for research projects on medicinal plants.

Podcasts and Web Series:

Expert Interviews: Conduct podcasts featuring interviews with experts, discussing medicinal plants' scientific and cultural aspects.

Web Series: Create a web series highlighting the stories of communities involved in medicinal plant cultivation.

Community Engagement:

Local Events: Organize community events and fairs focusing on Indian medicinal plants, involving local communities in cultivation and conservation efforts.

Field Trips: Arrange field trips to medicinal plant gardens and natural habitats for a practical learning experience.

Certification Programs:

Online Courses: Develop comprehensive online courses with certifications covering various aspects of Indian medicinal plants.

Skill Development: Include practical sessions in certification programs for hands-on skill development.

This integrated approach ensures that the learning process is dynamic and accessible and caters to a diverse audience, promoting a deeper understanding and appreciation of Indian medicinal plants.

Long-term importance of integrated media learning for Indian medicinal plants

The long-term importance of integrated media learning for Indian medicinal plants lies in fostering a sustainable and comprehensive approach to preserving, utilizing, and disseminating knowledge. Here are critical aspects of its long-term significance:

Cultural Preservation: Integrated media learning helps preserve traditional knowledge of Indian medicinal plants, ensuring that cultural practices and wisdom are passed down through generations.

Biodiversity Conservation: By educating individuals about the importance of medicinal plants, the learning process contributes to biodiversity conservation, protecting diverse plant species and their ecosystems. Community Empowerment: Empowering communities with knowledge about medicinal plants leads to sustainable practices, economic opportunities, and improved community health. This empowerment contributes to long-term social and economic development. Holistic Healthcare Integration: Integrating traditional knowledge with modern healthcare practices promotes a holistic approach to health. Over the long term, this integration can contribute to a more balanced and personalized healthcare system.

Environmental Stewardship: Learning about medicinal plants through integrated media emphasizes the importance of responsible environmental practices. This awareness encourages individuals and communities to be stewards of the environment, supporting long-term ecological health.

Innovation in Medicine: Continuous learning through integrated media can foster innovation in medicine. Traditional knowledge may inspire new avenues for drug discovery and the development of natural remedies.

Global Collaboration: A well-established platform for learning about Indian medicinal plants can facilitate international collaboration in research, conservation efforts, and knowledge exchange. This collaboration contributes to global advancements in healthcare and biodiversity conservation.

Adaptation to Climate Change: Knowledge about indigenous medicinal plants can help adapt to climate change. Understanding the resilience and properties of these plants may offer solutions for challenges posed by changing environmental conditions.

Education for Future Generations: Integrated media learning creates a foundation for future generations to understand and appreciate the importance of Indian medicinal plants. This sustained education ensures the continuity of efforts to responsibly conserve and utilize these resources.

Economic Resilience: Empowering individuals with skills related to medicinal plants contributes to economic resilience. As communities become adept at sustainable cultivation and processing, they can navigate economic challenges and capitalize on medicinal plants' economic potential.

In conclusion, integrated media learning for Indian medicinal plants is important because of its multifaceted contributions to cultural preservation, biodiversity conservation, community empowerment, and global collaboration. This approach sets the stage for a sustainable and harmonious relationship between people, medicinal plants, and the environment.

Benefits from the integrated media learning process for Indian medicinal plants

The integrated media learning process for Indian medicinal plants can benefit a diverse range of individuals and groups. Here are several stakeholders who can gain from such educational initiatives:

Traditional Healers and Practitioners: Access to integrated media learning enhances the knowledge and skills of traditional healers, allowing them to understand better and communicate the medicinal properties of plants.

Farmers and Agriculturists: Learning about cultivation methods, sustainable practices, and economic opportunities associated with medicinal plants can empower farmers and agriculturists to diversify crops and enhance agricultural practices.

Healthcare Professionals: Integrating traditional knowledge into the education of healthcare professionals fosters a more holistic approach to patient care, incorporating both modern medicine and traditional remedies.

Researchers and Scientists: Integrated media learning provides a valuable resource for researchers and scientists interested in studying the scientific properties of medicinal plants, potentially leading to discoveries and innovations.

Students and Educators: Comprehensive modules on Indian medicinal plants can benefit students and educators at both the school and university levels, enriching their understanding of traditional practices, biodiversity, and sustainable development.

Community Leaders and Organizations: Community leaders and organizations can utilize integrated media learning to spearhead local initiatives, promoting sustainable cultivation, conservation, and economic development within their communities.

Environmentalists and Conservationists: Knowledge about medicinal plants' significance contributes to environmental awareness. Conservationists can use this information to advocate for protecting natural habitats and biodiversity.

Pharmaceutical Industry Professionals: Professionals in the pharmaceutical industry can gain insights from integrated media learning for potential drug discovery and development, exploring the traditional uses of medicinal plants.

Tourism Industry: The tourism industry can benefit by incorporating educational components about medicinal plants into eco-tourism initiatives, attracting visitors interested in traditional knowledge and sustainable practices.

General Public: The general public stands to gain by understanding the cultural, ecological, and health-related aspects of Indian medicinal plants. This knowledge can lead to informed choices about healthcare and lifestyle.

International Collaborators: Researchers, educators, and organizations globally can benefit from the insights shared through integrated media learning, fostering international collaboration in medicine, botany, and conservation.

Government Agencies: Government agencies responsible for agriculture, health, and environmental protection can use integrated media learning to formulate policies that support sustainable practices, biodiversity conservation, and traditional knowledge preservation.

In summary, the integrated media learning process for Indian medicinal plants has wide-reaching benefits, touching various sectors and individuals. It contributes to sustainable development, cultural preservation, and the well-being of local communities and the broader society.

In summary, the significance of Indian medicinal plants is multifaceted, encompassing cultural, ecological, economic, and medicinal aspects, making them a valuable resource for various fields. Indian medicinal plants hold immense importance due to their traditional healing properties. Integrating these into worldwide mass education through media can promote holistic healthcare awareness and sustainable practices. This collaborative learning approach can bridge traditional knowledge with modern understanding, fostering a global appreciation for the richness of herbal remedies and promoting ecological conservation.

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Chapter- 13

Diaphonization: Enhancing Efforts Toward Achieving SDGs 10, 14, and 15

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Keywords: Diaphonization, conservation, clearing & staining, Morphology, Phylogeny, Sustainable Development

Abstract:
Diaphonization, also known as clearing and staining, is an invaluable technique for visualizing and studying the skeletal structures of animals. This study explores the application of diaphonization to examine bone development and soft tissues and determine causes of death in various animal species. By rendering tissues transparent and selectively staining bones and cartilage, diaphonization allows for detailed observation of skeletal morphology without dissection, thus preserving the integrity of specimens. This method enhances the understanding of morphological and anatomical structures and aids in determining the phylogenetic relationships between species. Diaphonization directly contributes to achieving Sustainable Development Goal (SDG) 4 by improving educational tools, indirectly supports SDG 10 by reducing educational inequalities, and SDG 14 and 15 by providing knowledge about the habitat of different species. Additionally, it plays a significant role in research, conservation, forensic science, and embryological studies.

Introduction:

Diaphonization, also known as clearing and staining, is a remarkable scientific technique used to study the internal anatomy of organisms without the need for dissection. It is also employed to investigate causes of death in various species and was first developed in 1977 by

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scientists G. Dingerkus and L.D. Uhler (Chitra et al., 2020), this process involves rendering biological specimens transparent while simultaneously staining bones and cartilage with vibrant dyes, enabling detailed examination of internal structures. Though the technique was first introduced in the early 20th century, it has become an invaluable tool in zoology, developmental biology, and paleontology.

Diaphonization combines elements of chemistry and biology to preserve specimens and highlight their intricate features. Specific chemical solutions are used to make soft tissues transparent, providing an unobstructed view of skeletal and cartilaginous components (Rehman et al., 2015). This method offers insights into the anatomy and development of organisms and also serves as an effective tool for education, museum displays, and comparative analysis with model specimens.

Diaphonization typically involves several key steps: fixation, staining, and clearing. The specimen is treated with a preservative agent during fixation to prevent decomposition and maintain tissue integrity. In the staining step, dyes such as Alcian Blue for cartilage and Alizarin Red for bones are applied, creating a striking contrast against the now-transparent soft tissues (Dawson, 1926). Finally, the clearing step uses solutions like glycerin to render the tissues transparent, revealing the internal architecture in vivid detail.

Diaphonization provides a unique glimpse into the complexity of anatomy, allowing scientists and enthusiasts alike to deepen their understanding of the structural intricacies of life. Through this captivating process, we can explore the hidden beauty of nature and gain valuable insights into phylogenetic relationships and developmental patterns that shape the diversity of life on Earth.

Materials & Method

Diaphonization is a technique that makes biological specimens transparent while simultaneously staining specific tissues, usually for research and educational purposes. This process allows scientists and researchers to study the internal structures of organisms without dissection (Chitra et al., 2020). This process has four major steps, viz., fixation, staining, clearing, and mounting or preservation, The following steps are discussed below-

1. Fixation: The fixation process starts with a 10% formalin deep bath of dead specimens for a minimum of 2 weeks, which preserves their tissues and prevents decay. After that, it can be transferred to the next step, the staining method.

2. Staining: Specific dyes are used to stain different tissues. For example, Alcian Blue and Alizarin Red S are two dyes that are mostly used to stain bones and cartilage. Alizarin Red S binds to calcium, providing a clear contrast against cleared tissues. Alcian Blue is used to stain cartilage, highlighting cartilage structures distinctively against the transparent background (Lipman, 1935).

3. Clearing: First, trypsin digestion. In this process, trypsin digests the cell protein, and the tissue appears transparent. After that, the specimen is treated with a series of solutions, such as glycerin or other clearing agents, that render the transparent tissues much softer and more transparent. This step allows the stained structures to be visible through the now-translucent body of the specimen (Cumley et al., 1939).

4. Preservation / Mounting: The cleared and stained specimen can be mounted in glycerin and thymol crystal for viewing. Cleared and stained specimens are stored in glycerin, which maintains transparency and provides a medium for long-term storage.

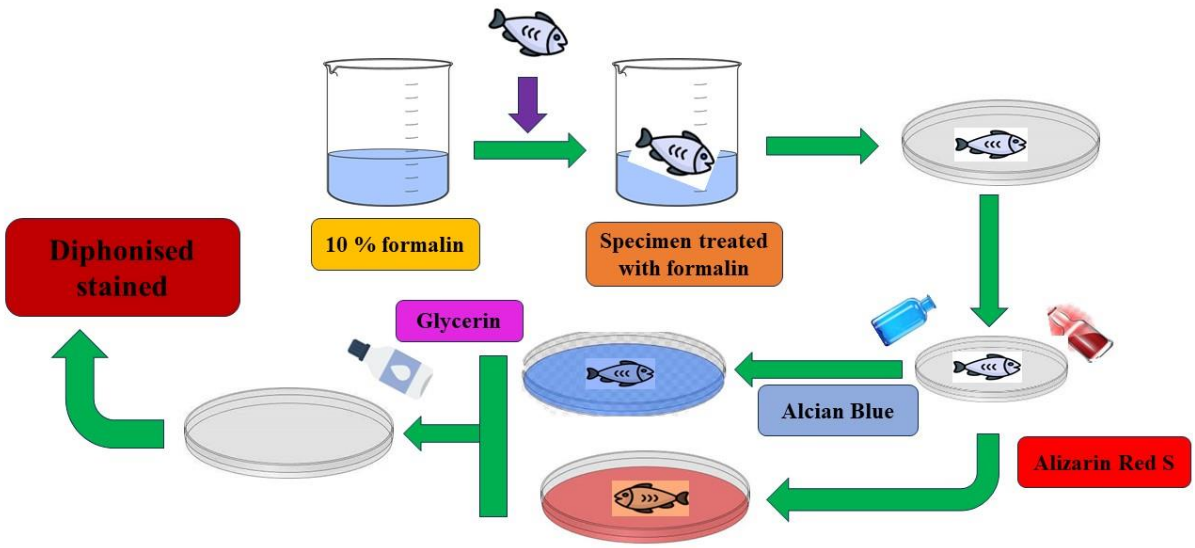

Figure 1. Method of diaphonization on a fish sample.

The Diaphonization Process can involve the following branches of biology:

Physiological System:

I. Vascular Staining: A dye such as Alcian Blue is often used to visualize the circulatory system. This dye stains glycosaminoglycans, which are present in the blood vessels, highlighting them in blue. Alternatively, specific vascular stains that bind to blood vessels can be used (Susaki *et al.*, 2020).

II. Optional Skeletal Staining: If both the circulatory and skeletal systems are to be visualized, Alizarin Red may be used to stain bones, allowing for a dual visualization.

The stained specimen is then treated with clearing agents, such as glycerol or benzyl alcohol/benzyl benzoate (BABB). These agents make the soft tissues transparent without disrupting the stained structures. Depending on the size and density of the specimen, the clearing process can take several days to weeks (Lee,1963).

Developmental Biology:

I. **Embryonic Development:** Studying the circulatory system development in embryos helps researchers understand congenital disabilities and the fundamental processes of vascular formation (Rueda-Esteban et al., 2017).

II. **Growth Patterns:** Observing changes in the circulatory system over developmental stages provides insights into growth-related changes and how they correlate with overall organismal development (Rueda-Esteban et al., 2017).

Evolutionary study:

- **Phylogenetic Relationships:** Diaphonization supports the reconstruction of evolutionary relationships by enabling the comparison of anatomical features across species, making it a valuable tool for phylogenetic studies.
- **Adaptations and Evolution:** By examining anatomical, morphological, and physiological traits, diaphonization aids in understanding the adaptive features of different species. It is also used to determine the ancestors of various species through parsimony analysis, which ultimately helps construct phylogenetic relationships.

Paleontological studies:

Diaphonization is a powerful tool that bridges the gap between modern organisms and their ancient counterparts. By studying the internal structures of modern analogs, paleontological studies can infer the structural anatomy, function, and evolutionary pathways of fossilized species.

Osteological and chronological study:

Diaphonization offers several advantages for studying bone and cartilage:

- **Enhanced Visibility:** The technique allows for the clear visualization of bone and cartilage structures, which can be challenging to distinguish with traditional imaging methods.
- **Non-destructive Analysis:** Unlike dissection, diaphonization preserves the specimen, enabling detailed study without damaging or altering the original anatomy.

Figure 2. Morphology of the bones and cartilage of a tetra fish using the diaphonization technique.

Applications of Diaphonization:

1. Developmental Biology:

- **Skeletal Development:** Diaphonization allows researchers to study the development of the skeletal system from embryonic stages to adulthood, revealing patterns of bone ossification and cartilage formation.
- **Congenital Defects:** The technique identifies and understands congenital skeletal abnormalities and malformations in embryos, providing insights into developmental disorders.

2. Comparative Anatomy:

- **Species Comparison:** Diaphonization helps researchers understand evolutionary adaptations and morphological variations by comparing bone and cartilage structures across different species.
- **Functional Morphology:** The technique provides insights into how skeletal structures are adapted for specific functions, such as locomotion, feeding, or flight.

3. Contributing to Species Recovery Programs:

- **Studying Endangered Species:** Diaphonization is particularly useful for studying endangered and threatened species. It provides critical information about their biology and ecology, which informs conservation strategies.
- **Guiding Breeding Programs:** By understanding anatomical and developmental aspects, conservationists can develop better breeding programs for endangered species, ensuring genetic diversity and health.

4. Contributing to Species Recovery Programs:

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5. Cause of death determination

This technique allows for a detailed examination of skeletal structures without dissection. While diaphonization is not typically used directly for determining the cause of death, it can be a complementary tool in forensic investigations and biological studies to provide insights into certain aspects of an organism's death or condition at the time of death.

Diaphonization can assist in determining the cause of death in two ways are

a. **Fractures or Trauma:** The process can reveal fractures, dislocations, or other skeletal injuries that might indicate trauma, accidents, or violence leading to death.
b. **Bone Density Analysis:** Conditions like osteoporosis or nutritional deficiencies can be observed, providing clues about the individual's health before death.

6. Role of Diaphonization in Achieving Sustainable Development Goals (SDGs)

Diaphonization plays a significant role in advancing several Sustainable Development Goals (SDGs) through its applications in research, education, and conservation:

SDG 4 (Quality of Education):

Diaphonization is a valuable technique used in research and education to render biological tissues transparent while selectively staining specific structures, such as bones and cartilage. This process enables detailed visualization of anatomy without dissection, making it especially useful in developmental biology and comparative anatomy. By providing clear views of skeletal structures and circulatory systems, diaphonization helps researchers and students observe bone and cartilage development and anatomical abnormalities. Diaphonized specimens in educational settings allow students to better understand spatial relationships within intact organisms, offering a practical, visual complement to textbook learning.

SDG 10 (Reduced Inequalities):

Diaphonization lowers costs and contributes to reducing inequalities in education. It provides durable, reusable anatomical specimens, reducing the need for costly live animals and dissection materials. These high-quality models improve learning efficiency, decreasing reliance on supplementary resources. Furthermore, digitized diaphonized specimens can be shared widely in virtual classrooms, making quality education accessible to students in resource-limited areas.

SDG 14 (Life Below Water) & SDG 15 (Life on Land):

Diaphonization aids in understanding the adaptive features of various species, providing valuable insights into their habitats and ecological diversity. By visualizing the internal structures of species from different environments, this technique enhances our knowledge of biodiversity and helps inform conservation strategies. Consequently, diaphonization supports the preservation of species and ecosystems, aligning with the goals of conserving marine (SDG 14) and terrestrial life (SDG 15) (Mukherjee et al., 2022).

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Chapter- 14

Role of Artificial Intelligence in Biological Research: A Short Review

Kaushik Sarkar

Keywords: Artificial Intelligence, Machine Learning, Biological Research, Disease Detection, Biomedical Imaging

Abstract:

Artificial Intelligence (AI) is simply machine learning (ML), a modern technology that handles various tasks that humans typically perform. This article aims to demonstrate the significance of AI in biological research science. Because of its ability to interpret data clearly, customize treatment strategies based on data representation, and optimize administrative processes, artificial intelligence (AI) has become increasingly important in the twenty-first century. However, some lacunae also exist due to their application in various fields, including biological research. However, this machine-learning technique enables the examination of various disease histories, the detection of diseases, etc. For research purposes, it also helps **to** make 3D structures of proteins, biomedical imaging, molecular formation, etc. By utilizing this AI technology, various nations improved their therapeutic techniques. As a result, the review article will help us **to** learn more about the application of AI technology in our educational system and research.

Introduction:

Not only in biological research but also in other fields today, scientists in different fields are involved in developing their techniques and tools using AI technology. Many industries use AI to upgrade their systems, such as healthcare, banking, gaming, robotics, virtual assistants, self-driving cars, fraud detection, and recommendation systems. In biology, scientists are dependent on AI to solve various challenging issues. Though it can be tough to understand how AI works on biological systems, it is a new idea in our modern era. A remarkable development in biological research was observed in the late **18th** century and early **19th** century (Figure 1) (Bhardwaj et al., 2022). It is considered the most demanding science because of its advanced technologies that save human lives, particularly by developing various health medicines. The connection between biology and computer science involves computing various biological data to solve problems and take concrete solutions. This multidisciplinary approach, known as computational biology or bioinformatics, is critical for analyzing extensive biological data, making it easy to decide on any drug discovery or advanced technologies.

About Artificial Intelligence (AI)

AI is the machine-learning process where a set of algorithms enables a computer to act as a human. It has two main subsets: machine learning and deep learning (Figure 2). Machine learning is the process where the computer can learn from data efficiently without any

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particular programming input. In machine learning (ML) algorithms are instructed in machine learning to create models using sample data so they can go on to make predictions or judgments (Camacho et al., 2018; Dawn et al., 2022; Dawn et al., 2023). A further branch of machine learning called "deep learning" uses a "neural network" to simulate how people process information and make decisions. Deep learning techniques expand upon research on artificial neurons, first proposed to simulate real biological brains in the 1940s (Ching et al., 2018; Hassoun et al., 2022).

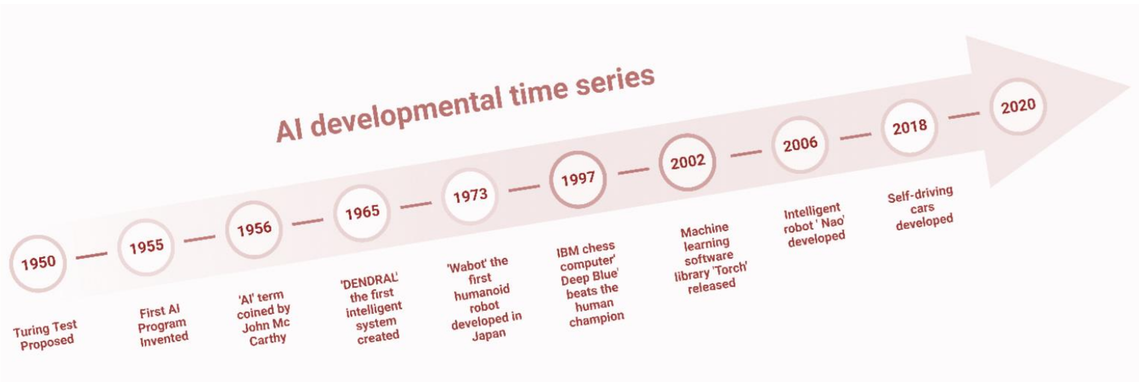

Figure 1. A sequence of events highlighting significant developments in artificial intelligence and their applications (Source: Bhardwaj et al., 2022).

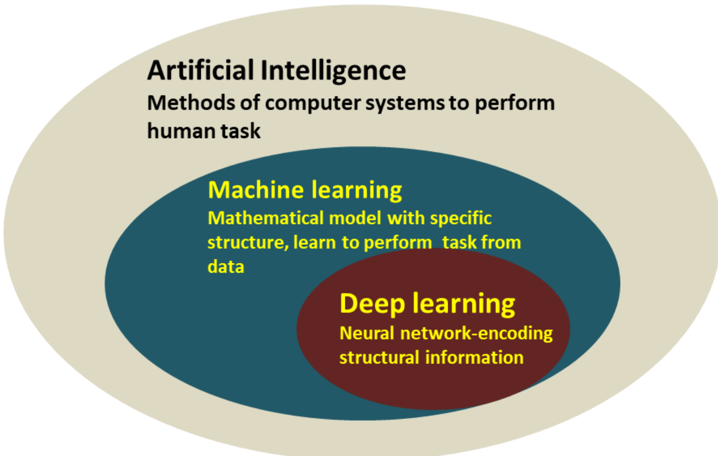

Figure 2. Structural relationship between artificial intelligence, machine learning and deep learning. (Source: https://bitesizebio.com/64186/artificial-intelligence-in-biology/ & CRS Report R47849. Artificial Intelligence in the Biological Sciences: Uses, Safety, Security, and Oversight. November 2023. https://crsreports.congress.gov).

In the recent era, humans benefit differently as AI and biology work together. It gives up facilitating research and development opportunities, which can scrutinize vast biological data and detect them, further correlating with **human's** nature of work. Thus, AI may be used in various biological fields such as genetic engineering, drug design and development, protein structure detection, critical diseases and their operation, etc., which are discussed further in this review section.

Some Applications of AI in Biological Research

Several search engine tools have observed that the number of AI search results in PubMed has increased daily, as mentioned in Figure 3.

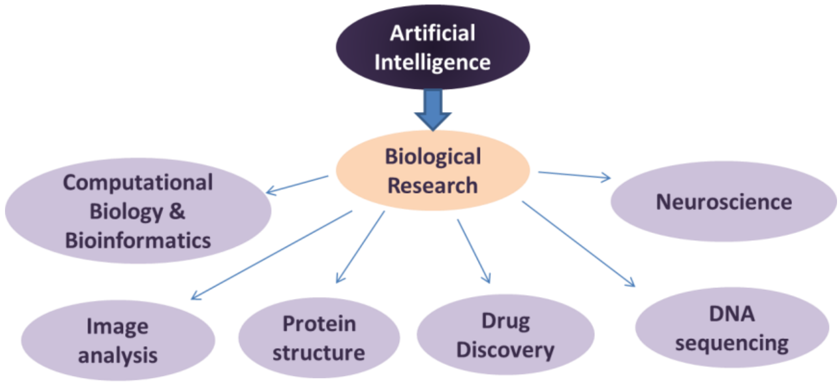

Figure 3. Some applications of AI in the field of biological research.

Application of AI in neuroscience:

Like the human brain, ML algorithms play a critical role in neuroscience. It plays a vital role in processing data in the visual cortex, neural plasticity, episodic memory etc. An important step towards understanding how the brain performs complex functions like face recognition is that artificial neural networks (ANNs) give neuroscientists ample models to explain how neural activity in different brain areas is performed (Koulakov et al., 2021). For experimental analysis, an animal given a series of stimuli and responses from different regions were recorded, which can be further used to compare the accuracy of the responses produced by various ANNs. Frequently, a neurone is modeled as a linear combination of ANN units, and the amount of variance in the neural response that the linear model explains is then determined (Savage, 2021; Richards et al., 2022; Kudithipud et al., 2022).

AI used for prediction of protein structure:

Different software tools were developed to analyze the protein structure. One of the most revolutionary protein structure detection software as a consequence of amino acid sequencing is AlphaFold. This is the leading software used for the first time to predict near-native protein folds from their genetic sequence. With the succession of AlphaFold software a few months later, the analog RoseTTAFold along with AlphaFold has contributed to their success in that anyone interested in experimenting with these programs can download them for free due to their open-source nature (Gomes et al., 2022; Jumper et al., 2021; Baek et al., 2021).

Application of AI in Drug Discovery

A simple drug is any substance used to prevent disease, treatment, or any other abnormal condition with a minimal dose. However, discovering a drug is challenging and critical to establish and show its efficacy in a limited period; identifying the target takes a long time. Thus, AI can help smooth the drug discovery process at this time. In various aspects, AI can help a drug design a program to target the problem. In addition to its benefits, artificial intelligence poses serious data challenges, including data volume, growth, diversity, and unpredictability (Hassabis et al., 2017; Chen et al., 2018). In most cases, the main areas where AI is fruitful in drug discovery are predicting the properties of a potential compound accurately, developing new compounds by creating molecules with properties predicted for success, which could dramatically improve the discovery and development of effective new drugs, eliminate repetitive tasks when assessing a drug's effectiveness (Jumper et al., 2021; Preuer et al., 2019). Furthermore, AI-based algorithms can also be employed to identify new targets for drug development, such as the specific proteins or genetic pathways involved in diseases (Paul et al., 2021). In medical chemistry, AI is used to predict the efficacy and toxicity of potential compounds. The mode and pattern of action of a drug can be identified by AI-based analysis by ML algorithm, which could not be possible by human scientists (Blanco-González et al., 2023). Using these techniques, a bioactive compound's efficacy with a very minimal dose can be identified easily. On the other hand, AI is also used to identify a broad spectrum interaction between two drugs or multiple drugs with their trends and patterns of reaction (Blanco-González et al., 2023; You et al., 2019; Hansen et al., 2015; Gómez-Bombarelli et al., 2018). Thus, we can state that artificial intelligence (AI) is utilized in drug discovery processes such as target identification, drug molecular simulation, drug designing, and drug assumption of properties for subsequent pathway synthesis generation.

Application of AI in DNA sequencing

DNA sequencing, also known as genomic sequencing, is an experimental method scientists use to ascertain the precise nucleotide sequence of a DNA molecule. The machine methods for sequencing DNA have certain limitations and require much time. On the other hand, application AI can aid in data integration, sequencing variation, and the reduction of errors during the DNA sequencing process. This data variation aids in the discovery of customized medication to treat genetic illness (Chen et al., 2018; Qureshi et al., 2023; Vilhekar and Rawekar, 2024; Heather et al., 2016; Xu et al., 2019; Racovita and Jaramillo, 2020).

Application of AI in biological image analysis

Biological imaging is a non-invasive process where researchers can observe the biological data visually in a large section and analyze the data. Thus, the AI helps to analyze the extensive data from an image and extract the result, which can facilitate the scientist to interpret the result of their observation obtained from the bio-imaging. The fields of bio-imaging where AI technology can be beneficial are microscopy, molecular imaging, pathological imaging, optical coherence tomography, nuclear medicine, ultrasound imaging, X-ray radiography, CT-scan, magnetic resonance imaging (MRI), etc. (Xu et al., 2021; Dias and Torkamani, 2019; Carreras-Puigvert and Spjuth, 2024; Li et al., 2024; Bhardwaj et al., 2022; Maqsood et al., 2024). One of the most essential tools in using machine learning technology in bio-imaging is "Aivia." These ML tools are used to arrange objects and pixels in an image by using deep learning technology, which can further restore the image resolution and extract essential information for speedy learning to identify any infectious diseases or conditions (Xu et al., 2021).

Application of AI in Computational Biology and Bioinformatics

Computational biology and bioinformatics are two significant fields in the biological research sector of modern science that analyze biological data using large-scale computer-generated mathematical calculations. As a result, this industry is vast in which ML algorithms using AI-based technology can be applied. The development of artificial intelligence (AI) in bioinformatics has opened up a wide range of knowledge about RNA, DNA computing, genomic sequence, gene expression regulation, and protein data processing, among other topics. Without this technology, it is challenging to conduct large-scale theoretical studies of the structures of proteins, RNA, and DNA, which makes it easier to develop new drugs and put them to use (Lai et al., 2018; Alam et al., 2024; Karim et al., 2023; Narayanan et al., 2002; Ezziane, 2006).

Conclusion:

It is evident now from AI's discoveries and applications that AI may be essential for biological and medical research. Numerous applications of machine learning in various biological fields have shown that AI is essential to overcoming the difficult task of analyzing large amounts of biological data, which is nearly impossible for researchers working by hand. However, there are some drawbacks to using AI in machine learning. Because machine learning is involved, calculations may occasionally miss the main issue, and the application will stray from its intended purpose. Applying AI to human research raises additional ethical concerns. This review paper provides information about the benefits of applying AI to our biological research system, which is essential for conducting theoretical and mathematical analyses of large amounts of data, even though it ignores some of its drawbacks. Following analysis, the data's conclusions may be applied to people to improve their quality of life.

Conflict of Interest:

The author declares no conflict of interest.

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Chapter- 15

A Scoping Review on the Effects of Psychological Stress on Working Memory: Insights into Sustainable Development Through Mental Health

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Keywords: Young adult, SDG17, Mental health, Memory, Cognitive development, Mental wellbeing

Abstract:
Sustainable development is essential for the preservation of natural resources. A total of 17 Sustainable Development Goals (SDGs) have been adopted by the United Nations, with the third goal focusing on promoting health and well-being. Mental health is an inseparable part of overall health; therefore, mental well-being is crucial for an individual's well-being. If mental well-being is compromised, it can lead to mental disorders such as depression, anxiety, and stress. It is well-known that mental illness can alter the structure of various parts of the brain, such as the hippocampus and amygdala, which are involved in memory processes. Psychological stress is often the initial phase of mental illness. Investigators have reported inconsistent findings on the effect of psychological stress on working memory. While most studies have shown that psychological stress negatively affects working memory, a few reports have indicated no relationship or even a positive relationship between the two. In India, there is a lack of evidence in the literature addressing the relationship between psychological stress and working memory. More research is needed to fully understand psychological stress's impact on working memory. Psychological stress management programs are necessary to prevent long-term mental illness. Additionally, mental health policies should be formulated to promote mental well-being. Ultimately, mental wellness will contribute to improved socio-economic conditions in any country.

Introduction:

Sustainable development can be defined in many ways. According to the International Institute for Sustainable Development, sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (International Institute for Sustainable Development, 2024; Saha, 2023; Moitra et al., 2023; Mukherjee et al., 2022; Chatterjee et al., 2023). Among the 17 Sustainable Development Goals (SDGs) adopted by the United Nations, the third goal is to "ensure healthy lives and promote well-being for all at all ages" (United Nations, 2024). Sustainable Development Goal 3 (SDG 3) aims to promote health and well-being (World Health Organization, 2024b). Overall health includes both physical and mental health (Centers for Disease Control and Prevention,

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2024). Mental health is an essential and integral part of human well-being, without which overall well-being cannot be achieved (World Health Organization, 2024a).

Mental illnesses include conditions such as depression, attention deficit hyperactivity disorder (ADHD), autism, and obsessive-compulsive disorder (OCD) (National Institutes of Health (US) & Biological Sciences Curriculum Study, 2007). Research on patients with mental illness has revealed that mental illness can alter the structure of different parts of the brain (National Institutes of Health (US) & Biological Sciences Curriculum Study, 2007; Dixit et al., 2024; Sapharina et al., 2024). The hippocampus and amygdala are brain regions that play a major role in memory. Reduced hippocampal volume and hyperactivity of the amygdala have been observed in adults with depression (Dillon and Pizzagalli, 2018). It has also been observed that patients with depression secrete less serotonin in the synaptic cleft compared to individuals without depression (National Institutes of Health (US) & Biological Sciences Curriculum Study, 2007). Serotonin plays an important role in working memory (Cano-Colino et al., 2013). Therefore, individuals with depression are prone to experiencing a decline in memory function (Dillon and Pizzagalli, 2018). The current review aims to examine the effect of psychological stress on the working memory of young adults.

Methodology:

The PubMed database was searched using keywords such as ‘mental health,’ ‘psychological stress,’ ‘working memory,’ and ‘young adults.’ The Boolean operator AND was used to combine these terms.

Mental health:

Mental health can be defined as a state of mental well-being (World Health Organization, 2024a) and the absence of psychopathologies such as depression, anxiety, etc. (Westerhof and Keyes, 2010; Singh et al., 2023; Kaur et al., 2023; Lakshmi et al., 2024). Mental well-being helps combat psychological stress and enables individuals to perform well in all aspects of life (World Health Organization, 2024a). It is essential for overall well-being, encompassing emotional, social, and psychological dimensions (Westerhof and Keyes, 2010). Mental well-being is also associated with a reduced mortality rate in both healthy and diseased individuals (Chida and Steptoe, 2008).

Several factors act as protective factors for mental health. Employment, physical activity, and diet are identified as key protective factors (Heinsch et al., 2022). Poor mental health has numerous adverse effects, including poor academic performance, violence, and poor reproductive health (Patel et al., 2007). The disruption of psychological processes may lead to mental disorders (Kinderman, 2005). Mental illness can alter an individual’s thinking, behavior, or feelings (National Institutes of Health (US) & Biological Sciences Curriculum Study, 2007). Psychological stress, also known as mental illness, can impair cognitive functions, such as working memory, in individuals (Qin et al., 2009).

Working memory:

Working memory can be defined as a small amount of information that is readily accessible and can be used to perform cognitive tasks (Cowan, 2014). It plays a vital role in learning, cognitive development, idea complexity, processing speed, and more (Cowan, 2014). Furthermore, working memory is crucial for logical reasoning, problem-solving, decision-making, and information processing (Cowan, 2014; Sankalaite et al., 2023). Different brain cortex regions are involved in working memory, including the prefrontal, cingulate, and parietal cortices (Chai et al., 2018). Some subcortical regions, such as the midbrain and cerebellum, are also engaged in the working memory process (Chai et al., 2018).

Several factors can influence working memory, such as genetics, mental illness, psychological stress, hormones, sleep, and exercise (Blasiman and Was, 2018; Chai et al., 2018). Psychological stress is one of the most significant factors among them. Acute stress can impair working memory processing (Luethi et al., 2009), negatively affecting information processing (Luethi et al., 2009). Moreover, glucocorticoid administration, used as a treatment for stress, has been shown to impair working memory (Luethi et al., 2009). Working memory positively correlates with academic performance (Hussain et al., 2023). Therefore, it is crucial for all types of students.

Relationship between psychological stress and working memory:

Acute stress can modulate working memory through the action of glucocorticoid and mineralocorticoid receptors located in the prefrontal cortex, amygdala, and hippocampus (Oei et al., 2006; Roozendaal et al., 2009). Everyday stressors may decrease working memory (Sliwinski et al., 2006). Authors from different countries have reported the effect of psychological stress on working memory, but with inconsistent findings (Table 1).

Table 1. Studies on the effect of psychological stress on working memory of young adults.

Author	Age of Participants (Mean ± Standard Deviation)	Location of the Study	Effect of Psychological Stress on Working Memory
Oei et al., 2006	21.86 ± 3.89 years	Amsterdam	Impair under high load
Lupien and Hauger1999	23.3 ± 3.5 years	San Diego	Acute stress affects working memory but not declarative memory
Luettgau et al., 2018	26.62±5.16	Leipzig	Acute stress negatively affects working memory
Lukasik et al., 2019	18-65 years	America	No relationship between acute stress and working memory
Sliwinski et al., 2006	80.23± 6.30 (older adults) 20.21 ± 1.09 (young adults)	Syracuse	No effect of stress on working memory

Domes et al., 2001	47.3±10.3 years	Germany	No relationship between stress and non-declarative memory Positive correlation between stress and declarative memory
Singh and Teotia, 2020	18-25 years	National Capital region, India	There is a relationship between anxiety and working memory

To test whether psychological stress could impair working memory, a study was conducted on 20 young, healthy first-year psychology students from the University of Amsterdam (having a body mass index between 19–25 kg/m², with no medical or psychological history). It was reported that psychosocial stress may result in poor working memory performance under high loads but not under low loads (Oei et al., 2006). Lupien and Hauger (2009) conducted a study on 40 young men from the University of California to investigate the effect of psychological stress on a working memory task, a declarative memory task, and a continuous performance task (Lupien et al., 1999). It was found in that study that stress had an acute effect on working memory but did not significantly affect declarative memory.

Another study was conducted on 34 healthy individuals at the Max Planck Institute for Human Cognitive and Brain Sciences to determine the effects of intra-individual stress on working memory (Luettgau et al., 2018). It was found that past subjective stress negatively affected working memory. However, there was no difference in the performance of intra-individual working memory due to acute stress or related stress reactivity (Luettgau et al., 2018). Psychological stress has also been shown to affect forgetfulness (Sandi, 2007). In a study conducted on college students in Egypt, it was found that students with high levels of psychological stress scored significantly lower than their peers with lower levels of psychological stress (Abo Hamza and Helal, 2021).

Interestingly, contrary to previous studies, some reports mention no relationship between psychological stress and working memory. In a study carried out on 503 American adult participants, aged between 18–65 years, it was found that working memory had a negative relationship with anxiety. However, no relationship was found between working memory and stress (Lukasik et al., 2019). Similar results were reported by Domes et al. (2001), who found no effect of stress on non-declarative memory performance. Moreover, stress-induced cortisol levels positively correlated with declarative memory (Domes et al., 2002). Another study conducted on 108 older adults and 68 young adults from Syracuse also found no effect of stress on working memory (Sliwinski et al., 2006).

In India, reports on the effect of psychological stress on working memory are very limited. A study was conducted on 140 young adults aged 18–25 in the National Capital Region of India (Singh and Teotia, 2020). In that study, a significant relationship was found between anxiety and working memory, though it was not specified whether the correlation was positive or negative. More studies are required from India to establish the effect of psychological stress on the working memory of young adults.

Conclusion:

From the above literature, it is evident that psychological stress definitely impacts working memory. In some cases, psychological stress negatively affects working memory, while in others, there is no significant effect. Since working memory is influenced by acute and temporary factors such as emotional conditions and brain stimulation, there is potential for modification of an individual's emotional state (Blasiman and Was, 2018). The emotional condition of a psychologically stressed individual can be improved through stress management intervention programs. It has been shown that stress management interventions can enhance the working memory of college students (Klein and Boals, 2001).

In addition to psychological stress management programs, mental health policies—such as endorsing mental health goals, promoting well-being, and preventing and treating mental disorders—can be formulated to support mental health. These policies will assist mentally ill individuals in achieving healthy social and psychological functioning. Regularly planning psychological stress management intervention programs and mental health policies is essential to reduce the burden of psychological stress on young adults, representing any country's future. As mental health is a key pillar of sustainable development goals, significant emphasis should be placed on the mental well-being of individuals. Ultimately, this will contribute to an improved socio-economic condition in any nation.

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Chapter- 16

Supercapacitor: An Offer to Sustainable Green Energy

Nirmalendu Hui

Keywords: EDLC, Pseudocapacitor, Hybrid capacitor, Power density, Energy storage system

Abstract:
With the increasing demand for sustainable green energy to minimize environmental pollution and reduce the use of fossil fuels, it is imperative to find alternative, environmentally friendly approaches to efficiently manage energy conversion and storage systems. In this context, supercapacitors or ultracapacitors have garnered significant attention, not only due to their high power density, high capacity with low internal resistance, rapid charging and discharging processes, and long life expectancy but also due to their environmentally friendly nature. The most widely used storage devices are batteries, which contain heavy metals such as zinc, lead, manganese, and mercury. These heavy metals cause long-term severe environmental pollution. In contrast, the waste management of supercapacitors is environmentally safe, as no heavy metals or harmful chemicals are used. The advent of hybrid capacitor technology and the discovery of graphene have made this technology even more attractive. This chapter briefly discusses the characteristics, basic storage principles, advantages, limitations, and scope of applications.

Introduction:

In today's world, everyone relies on energy at every second and in every aspect of life. It is impossible to imagine a day without energy. To meet our energy demands, we predominantly use fossil energy. Fossil fuels such as coal, oil, natural gas, and their derivatives like kerosene and gasoline are primarily hydrocarbons. These fuels are found in the earth's crust and formed when prehistoric plants and animals decompose due to heat and pressure. These non-renewable energy sources are used to fulfill our daily energy needs at both the industrial and domestic levels. Since the Industrial Revolution in Great Britain in the 18th century, fossil fuel consumption has increased exponentially. Today, over 80% of the world's primary energy consumption and over 60% of its electricity come from fossil fuels.

The overuse of these hydrocarbon-rich fossil fuels has two major impacts: Firstly, the sources of these non-renewable fuels are rapidly depleting, as their formation requires a geological process that spans millions of years. Secondly, they emit greenhouse gases such as CO, CO_2, and CH_4, which cause significant environmental harm, including global warming and pollution (Wang et al., 1976; Parikh and Shukla, 1995; Gerlich and Tscheuschner, 2009). In response, scientists, engineers, and world leaders are seeking solutions to the problems posed by fossil fuels to create a healthier environment with sufficient clean energy to sustain human life and activities in the future.

This growing necessity has driven research into various types of renewable energy sources, such as solar energy, wind energy, tidal energy, hydroelectric energy, biomass energy, and nuclear energy (Rugani et al., 2011; Liu et al., 2019; Hussain et al., 2017; Demirbaş, 2006; Yüksel, 2010; Abbott,

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2012). These sources offer environmentally friendly, clean, and virtually unlimited power. However, despite the availability of these alternatives, daily energy consumption still largely depends on fossil fuels due to inherent production challenges and other issues.

In this context, energy storage devices play a crucial role. Since ancient times, various storage systems, including pumped hydro, thermal energy, compressed air, flywheels, electrochemical, chemical, and superconducting magnetic systems, have been used (Hossain et al., 2020; Sharma et al., 2009; Rehman et al., 2015; Guo et al., 2021; Olabi et al., 2021; Gür, 2018; Boom and Peterson, 1972; Mitali et al., 2022). Among them, batteries, which are electrochemical energy storage systems, are widely used in sectors ranging from industry to everyday life.

In this digital age, most energy is consumed in the form of electricity. Currently, most electric energy is generated from thermal power, which relies on fossil fuels. Since fossil fuels negatively impact the environment, scientists have developed alternative technologies to convert various non-conventional energy sources, such as hydro energy, solar energy, wind energy, and wave energy, into electricity. The advancement of electric energy storage technology is crucial to reducing the use of conventional energy and ensuring proper storage of this electrical energy.

Therefore, to address the energy crisis and its associated environmental problems, we must focus on renewable energy sources and develop low-cost, environmentally friendly energy storage systems. In this context, one critical approach is replacing batteries with capacitors, another key concept of Green Electricity.

Backgrounds:

Both batteries and capacitors can store electrical energy. Generally, a battery is a system where two electrodes, called the anode (+ve end) and cathode (-ve end), are partly immersed in a vessel filled with an electrolyte solution. Energy is stored in a battery due to a net chemical reaction between the electrode and the electrolyte, which gives it a limited life cycle. However, the main advantage of batteries is their very high energy density. Although this makes them an automatic choice and popular for energy storage, they have a very low power density.

In energy storage systems, two terms are essential—energy density (or specific energy) and power density (or specific power). The first term refers to the amount of energy stored per unit mass or volume, while the second refers to the power per unit mass. Simply put, energy density indicates how much energy a system contains, and power density indicates how quickly it can discharge its energy. A system with a large energy density but low power density can deliver energy over a more extended period.

A conventional capacitor stores energy by charging and discharging, and since no chemical reaction is involved, it can be used millions of times, theoretically, even infinitely. It is a two-terminal electrical component. In general, when a dielectric (insulating) medium is placed between two parallel conducting plates, a capacitor is formed. Suppose the surface area of the parallel plates is A, the distance between the two plates is d, and the permittivity of the dielectric medium is $\mathcal{E}_0$. In that case, the capacitance (C) of this parallel plate capacitor will be:

$$C = \varepsilon_0 A/d \qquad (1)$$

Now, if the capacitor is connected to a voltage difference V, it will become charged. The amount of electrical energy (E) stored in the capacitor can be expressed as:

$$E = \frac{1}{2}CV^2. \qquad (2)$$

Thus, more capacitance means more energy stored in the capacitor. Generally, the capacitance of a conventional capacitor is very small (~µF), and as a result, the energy stored in it is also small. We would require huge dimensions to achieve a large capacitance (~F), which is practically impossible. Unlike a battery, a capacitor has low energy density but high power density, meaning it can deliver or absorb energy very quickly once it begins to discharge or charge. Therefore, both batteries and conventional capacitors have their respective advantages and disadvantages.

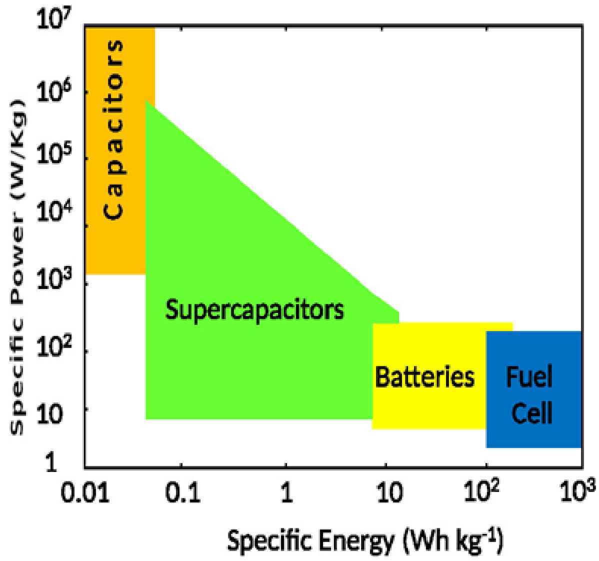

Figure 1. Ragone plot of energy storage device (Kotz and Carlen, 2000).

The technology of supercapacitors, or ultracapacitors, helps to bridge the gap between batteries and dielectric capacitors in terms of energy density and power density, as indicated in Figure 1 (Kotz and Carlen, 2000). Advances in supercapacitor technology have made it possible to achieve large capacitance (~F) in very small dimensions by utilizing electrode materials with high surface area and thin electrolytic dielectrics (Conway, 1999; Kotz and Carlen, 2000; Burke, 2000; Chu and Braatz, 2002; Aricò et al., 2005). The characteristics of high power density, moderately high energy density, exceptionally long life cycles, a wide thermal range (-40°C to 70°C), low weight, and low maintenance costs, compared to secondary batteries or conventional dielectric capacitors, make supercapacitors an attractive energy storage device (Wang et al., 2009). Compared to electrolytic capacitors, supercapacitors can store 10 to 100 times more energy per unit volume or mass. Since no chemical reaction occurs during charging and discharging, they can endure significantly more charge cycles compared to rechargeable batteries and accept and deliver charge much faster.

Classification of Supercapacitors and Energy Storage Mechanism:

Supercapacitors can be divided into three categories based on their charge storage mechanism: (1) Electrochemical Double Layer Capacitor (EDLC), (2) Pseudo-capacitor, and (3) Hybrid Capacitor. Figure 2 illustrates the taxonomy of supercapacitors based on storage mechanisms and electrode materials (Hadjipaschalis et al., 2009).

Electrochemical Double Layer Capacitor (EDLC):

The charge storage mechanism of an EDLC is a non-Faradaic process, similar to that of a conventional capacitor, where charges are accumulated electrostatically, and no charge transfer occurs between the electrode and the electrolyte. Consequently, the capacitance originates at the electrode-electrolyte interfaces. In electrochemical double-layer capacitors, an electrolyte (a mixture of positive and negative ions dissolved in a solvent, such as water) is used between two carbon-based electrodes instead of the dielectric medium used in conventional capacitors. For example, aqueous solutions of KOH, H_2SO_4, or Na_2CO_3 are common electrolytes. A separator allows ions in the electrolyte solution to diffuse into the electrode's pores with the opposite charge. A schematic diagram of an EDLC is shown in Figure 3.

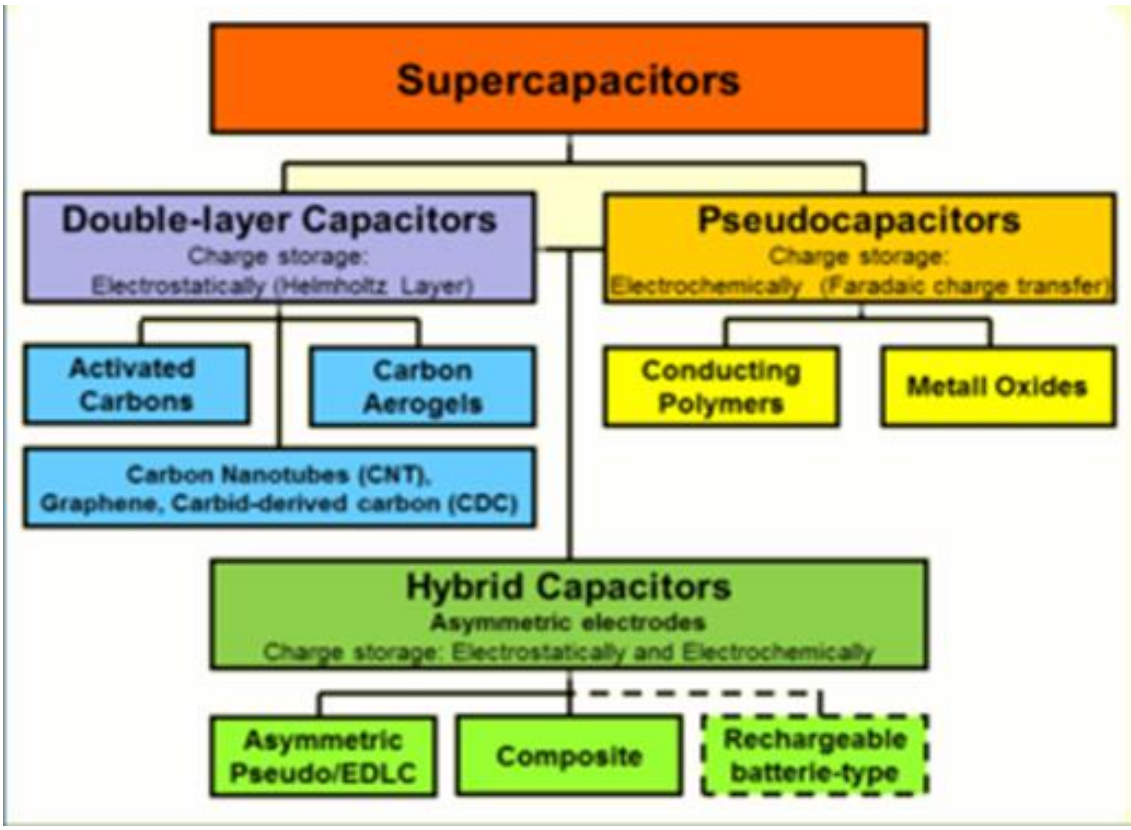

Figure 2. Classification of supercapacitors based on storage mechanism and electrode materials (Hadjipaschalis et al., 2009).

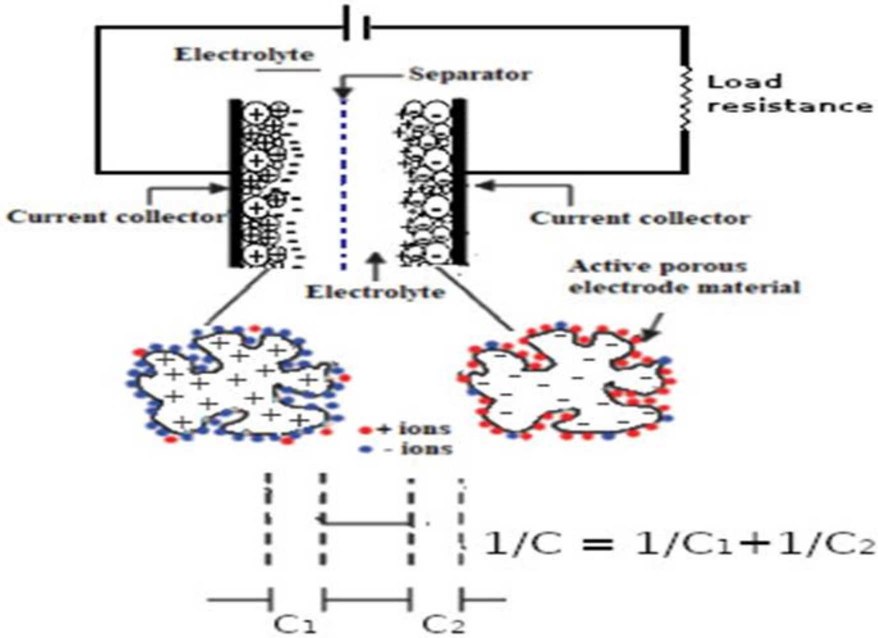

Figure 3. Schematic diagram of an EDLC with porous electrode materials (Zhang and Zhao, 2009).

In EDLCs, electrodes are engineered so that the recombination of ions or charges at the electrode-electrolyte interface is prevented (Shi et al., 2011). When voltage is applied, a double-layer of charge is formed due to the accumulation of ions in the electrode (e.g., negative ions) and solvated ions (e.g., positive ions) in the liquid electrolyte, which diffuses through a separator. A monolayer of polarized solvent molecules separates these. This double-layer acts approximately as the dielectric layer in a conventional capacitor, with a thickness of a single molecule. Therefore, the capacitance can be calculated using equation (1), which yields a very large value due to the minimal thickness (d) and large surface area (A). To achieve high storage capacity, it is essential to control the specific surface area, pore size, and enhance electrical conductivity (Wang et al., 2012).

Due to this charge storage mechanism, EDLCs achieve higher energy densities than conventional capacitors (Conway, 1999; Kotz and Carlen, 2000; Burke, 2000). Since, in EDLCs, each electrode-electrolyte interface acts like a capacitor, as shown in Figure 3, the system can be considered as two capacitors in series. This results in the cell capacitance (C), given by equation (3), where $C_1$and C_2 represent the capacitances of the first and second electrodes:

$$C = C_1\, C_2/(C_1 + C_2) \tag{3}$$

Here, $C_1$and $C_2$are the capacitances of the capacitors formed at the electrode-electrolyte interface, which depend on the nature of the electrode and electrolyte. The characteristics of EDLCs largely depend on surface area, pore size distribution, shape, structure, and conductivity. Electrodes with a porous structure exhibit a high specific area. Due to their higher surface area, lower cost, stability under high current loads, low internal resistance, and fabrication flexibility, carbon materials in different forms—such as activated carbons, carbon aerogels, carbon nanotubes, and graphene—are generally used as electrodes (Frackowiak and Beguin, 2001; Shi, 1996; Wang et al., 2001; Frackowiak and Beguin, 2002; Du et al., 2005; Gao, 2017; Zhang et al., 2014).

The electrolyte may be either aqueous or organic, depending on the intended application of the supercapacitor. No chemical changes occur since there is no charge transfer between the electrolyte and the electrode. Due to this, EDLCs are highly reversible and can operate for many charge-discharge cycles (as many as 10^6 times) with stable performance. Because of their cycling stability, EDLCs are well-suited for applications in non-user-serviceable locations, such as deep-sea or mountain environments (Conway, 1999; Kotz and Carlen, 2000; Burke, 2000).

Pseudo-capacitor (PC):

The energy storage mechanism of pseudocapacitors (PC) is based on a Faradaic charge process, which involves the transfer of charge between the electrode and electrolyte due to the oxidation or reduction of a chemical species. These Faradaic processes can be either reversible or irreversible. In reversible processes, no new chemical species are produced during redox Faradaic reactions, while in irreversible Faradaic processes, new species are generated. Generally, compared to electric double-layer capacitors (EDLCs), pseudocapacitors exhibit higher specific capacitance and energy density. However, pseudocapacitive electrodes commonly show poor electrical conductivity, restricting and slowing Faradaic reactions. This leads to lower power performance, reduced cycle life, and poorer mechanical stability than EDLCs (Hu et al., 2006; Ke et al., 2005). Notably, the response of pseudocapacitive materials is similar to that of double-layer capacitors. Conducting polymers and metal oxides are typically used for configuring pseudocapacitors.

Hybrid Capacitor:

Both Faradaic and non-Faradaic processes are used in hybrid capacitors to capitalize on the relative advantages and mitigate the drawbacks of EDLCs and pseudocapacitors. This concept achieves higher energy and power densities compared to EDLCs and higher cycle stability compared to pseudocapacitors. Depending on electrode configurations, there are three types of hybrid SCs: Composite, Asymmetric, and Battery-type. In battery-type hybrid capacitors, a battery electrode is used along with a supercapacitor electrode to achieve higher energy density, similar to batteries, while maintaining higher specific power, faster charging-recharging processes, and longer cycle life, like supercapacitors (Li et al., 2005).

Advantages and challenges of supercapacitors:

Advantages: Supercapacitors have several advantages over batteries:

- **High power density:** Compared to lithium-ion batteries (150 W kg^{-1}), supercapacitors display a much higher power delivery (1–10 kW kg^{-1}) as charging and discharging rates are much faster (~0.1–1 sec) than those of batteries (~hours) (Kusko and Dedad, 2007; Uzunoglu and Alam, 2006).

- **Long life expectancy:** No or negligibly minor chemical charge transfer reactions occur during charging and discharging. The life cycle of a supercapacitor is almost infinite (500,000–1,000,000 cycles) with no maintenance and a life expectancy of up to 30 years, whereas lithium-ion batteries have 1,000–10,000 cycles with a life expectancy of only 5–10 years (Conway, 1999; Burke, 2000; Zhang et al., 2009).
- **Long life:** Unlike rechargeable batteries, which experience self-discharge and corrosion, supercapacitors maintain their capacitance and recharging capabilities for several years (Burke, 2000).
- **Wide thermal range:** Supercapacitors can function effectively at a typical operating temperature of -40°C to 70°C. This is advantageous for military applications, where reliable energy storage is required to run proprietary electronic devices under all temperature conditions during warfare.
- **Environmental friendliness:** Supercapacitors are environmentally friendly as no hazardous or toxic materials are used, making the disposal of waste materials safe and easy.

Challenges:

Despite having many advantages over batteries, this technology has some limitations and faces several challenges:

- **Low energy density:** When compared with batteries (> 50 Wh kg^{-1}), supercapacitors have a low energy density (about 5 Wh kg^{-1}). This characteristic limits their use where a large energy capacity is required.
- **High cost:** One of the significant challenges for energy storage commercialization is the high costs of raw materials used as electrodes, electrolytes, and separators. Two common electrode materials used for commercial purposes, carbon materials with a high surface area and RuO_2, are costly, which makes supercapacitors costly (Burke, 2000).
- **High self-discharging rate:** The high self-discharging rate (about 10–40% per day) also hinders their practical uses.

Applications and scope:

With the advantages of high power density and an extensive lifecycle, supercapacitors are suitable for applications where high-power pulses for a short duration and many rapid charge/discharge cycles are required. Applications such as electric vehicles, digital cameras, mobile phones, GPS tracking systems, Bluetooth communication devices, digital communication devices, memory backup, medical equipment, forklifts, cranes, elevators, electrical tools, pulsed laser techniques, regenerative braking or burst-mode power delivery systems, uninterruptible power supplies, alarm and security systems, and storage of solar energy (Ming et al., 2010; Miller, 2006; Reddy and Reddy, 2003; Tehrani et al., 2017; Miller and Simon, 2008; Hu and Wang, 2003; Kim et al., 2015) are a few areas where supercapacitors are highly competitive choices. Under pulsed load conditions, supercapacitors act as filters that relieve peak stresses on the battery by supplying power to the system in short energy bursts. After delivering the pulse current, the battery quickly recharges the supercapacitor between pulse cycles. A parallel battery-supercapacitor connection greatly enhances peak power, considerably reduces internal losses, and extends the discharge life of the battery. With several advantages, supercapacitors have the potential to be a solution in the fields of energy conversion and storage systems by either replacing or complementing batteries.

Summary and Conclusion:

High power densities, quick charging and discharging processes, and exceptional cycle stability make supercapacitors a promising candidate in green energy solutions. This chapter briefly overviews supercapacitors and illustrates how they bridge the gap between capacitors and batteries. The basic charge storage mechanisms for different types of supercapacitors are discussed briefly. Although supercapacitors have many advantages, they face numerous challenges in practical applications. The discovery of graphene and carbon nanotubes has accelerated the development of this technology. With the constant advancement of new technologies and ongoing research into new materials for electrodes and electrolytes, supercapacitors are becoming a viable solution to the ever-increasing demand for clean, sustainable energy.

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Chapter- 17

An Ergonomic Approach to Sustainability for the Manual Material Handling Workers: A Review

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Keywords: Unorganised sector, Musculoskeletal Disorder, Awkward postures, Human factors, Occupational Health

Abstract:

Manual Material Handling (MMH) involves workers' physical handling of objects, such as lifting, carrying, pushing, or pulling. MMH activities can significantly contribute to the development of Musculoskeletal Disorders (MSDs) among workers. MSDs encompass a range of conditions affecting muscles, tendons, nerves, and joints due to repetitive movements, awkward postures, forceful exertions, or sustained exertions over time. In the context of MMH, workers often need help with ergonomic challenges, such as lifting heavy loads without proper techniques, working in awkward positions, or performing repetitive tasks without adequate rest periods. These factors increase the risk of developing MSDs, particularly in the upper limbs, lower back, and shoulders. To mitigate the risk of MSDs related to MMH, ergonomic interventions are crucial. These may include redesigning workstations and tools to reduce physical strain, training on proper lifting techniques, implementing task rotation to vary movement patterns, and promoting regular breaks to allow recovery. Effective ergonomic measures enhance worker health and safety, increase productivity, and reduce healthcare costs associated with MSDs in occupational settings. Integrating ergonomic principles into sustainable development strategies for MMH workers contributes to organizational sustainability by lowering absenteeism, healthcare costs, and worker compensation claims.

Introduction:

The term 'Ergonomics' originates from the Greek words 'ergon' (work) and 'nomos' (laws), signifying the study of work. Ergonomics is a holistic discipline that encompasses all facets of human activity. It is a scientific field focused on understanding how humans interact with various elements within a system. This discipline considers physical, cognitive, social, organizational, and environmental factors. Ergonomics utilizes theoretical principles, methodologies, and empirical data to enhance human well-being and system performance (Eklund, 1999; Gajbhiye et al., 2023a & b; Khant et al., 2023; Ranganathan et al., 2024a & b).

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Occupational health, according to the International Labour Organization (ILO) and the World Health Organization (WHO), encompasses health issues related to the occupation of any worker. Studies and interventions should aim at preventing such health hazards in the workplace, which may ultimately affect workers' physiological and psychological capacities. Specifically, interventions should promote physical, mental, and social well-being for every worker. In essence, it encourages the adaptation of work to individuals and individuals to their jobs (WHO, 1985).

Applying Ergonomics in the workplace offers numerous benefits. Workers experience healthier and safer working conditions, enhancing their overall well-being. Employers benefit from increased productivity, which directly results from low-cost Ergonomics interventions. These interventions can include organizational restructuring to realign workstations with strategic goals, and optimizing productivity. Additionally, proper tool design, rotating work schedules, work pacing, scheduling improvements, and exercise programs collectively contribute to both productivity enhancement and the promotion of human wellness (Johnson, 1993).

India experienced an industrial revolution towards the late 19th century, leading to the development of numerous industries. However, during this period, there needed to be more awareness regarding the health and safety of workers. In India, research in occupational health has been hindered by a need for more foundational data and inadequate funding availability (Gangopadhyay, 2012). In India, the projected number of workers in the unorganized sector in 2004-05 was approximately 390 million, contributing to around 85 percent of total workers, including all age groups below and above the average working age range (Naik, 2009). Nine out of ten workers in India work in the unorganized sector (Pandya and Patel, 2010). Despite their large numbers and significant contributions to the national economy, they remain one of the poorest segments of our population. Work in the unorganized sector is marked by low wages that often fall short of meeting basic living standards, including adequate nutrition. Workers typically face long hours, hazardous conditions, and a lack of essential services such as first aid, clean drinking water, and sanitation facilities. These workers do not receive the benefits of the Minimum Wages Act or the Factories Act.

Organized sectors in developing countries are mostly safe. This leads to Manual Material Handling (MMH)-related acute injuries and Musculoskeletal Disorders (MSDs). MSDs affect muscles, bones, and tendons, encompassing acute and chronic conditions based on their causative factors. Acute MSDs typically result from sudden muscular damage, often due to accidents. In contrast, chronic MSDs develop over prolonged periods due to ongoing exposure to risk factors associated with the work environment.

This review examines work-related musculoskeletal disorders (MSDs) among Manual Material Handling (MMH) workers in the unorganized sector. It seeks to identify the prevalence of MSDs and their correlation with various occupational risk factors such as job autonomy, working behavior and work-related stress. Furthermore, the review aims to explore the role of Ergonomics in promoting sustainable development among these workers by improving health outcomes.

Musculoskeletal Disorders – Definition and Risk Factors

Manual Material Handling (MMH) involves workers' physical handling of objects, such as lifting, carrying, pushing, or pulling. MMH activities can significantly contribute to the development of Musculoskeletal Disorders (MSDs) among workers. MSDs encompass a range of conditions affecting muscles, tendons, nerves and joints due to repetitive movements, awkward postures, forceful exertions, or sustained exertions over time. In the context of MMH, workers often face ergonomic challenges, such as lifting heavy loads without proper techniques, working in awkward positions, or performing repetitive tasks without adequate rest periods. These factors increase the risk of developing MSDs, particularly in the upper limbs, lower back, and shoulders. To mitigate the risk of MSDs related to MMH, ergonomic interventions are crucial. These may include redesigning workstations and tools to reduce physical strain, training on proper lifting techniques, implementing task rotation to vary movement patterns, and promoting regular breaks to allow recovery. Effective ergonomic measures enhance worker health and safety and increase productivity and reduce healthcare costs associated with MSDs in occupational settings. Integrating ergonomic principles into sustainable development strategies for MMH workers contributes to organizational sustainability by lowering absenteeism, healthcare costs, and worker compensation claims.

Manual Material Handling and Its Health Effects

The materials handling industry plays a crucial role in the global economy, yet it faces significant challenges related to occupational injuries and illnesses. Understanding the underlying risk factors and associated costs could help mitigate these issues. Manual Material Handling (MMH) is mainly linked to severe injuries, pain, disability, fatalities, and reduced productivity for workers and their families, leading to substantial economic losses for society as a whole. Extensive literature supports the notion that high physical workloads and hefty lifting, significantly increase the likelihood of these adverse outcomes (Andersson, 1997; Burdorf and Sorock, 1997; Gordon and Weinstein, 1998; Hoogendoorn et al., 1999; Marras, 2005; Myers et al., 1999; National Research Council (US) and Institute of Medicine (US), 2001). Similarly, the wide variety of musculoskeletal disorders (MSDs) affecting the upper and lower extremities is linked to various physical exposures, including manual material handling (MMH) (Putz-Anderson et al., 1997).

Injuries related to MMH have grown significantly. These injuries can occur from lowering, lifting, pulling, pushing, etc., along with environmental interactions like slipping and falling (Tayyari and Smith, 1997). Heavy MMH activity is associated with the risk of developing MSDs. A study in the aluminium industry of Iran showed that about 66% of respondents in the last week and 78% of respondents in the last year reported suffering from at least one musculoskeletal issue. The most prevalent body parts involved were the lumbar region, knees, and upper back. These complaints had significant associations with job duration and the age of the workers (Aghilinejad et al., 2012).

MMH is a significant contributor to the expenses of compensable workplace injuries. The current MMH guidelines (Snook and Ciriello, 1991) were developed based on maximum acceptable weights and forces. The experiments were carried out over a 21-year period before the results were published, raising the question of whether these guidelines are relevant for today's workers.

More than 70% of Indians are engaged directly in MMH activities. Therefore, even a slight improvement in working conditions would benefit millions of Indian people (Sen and Nag, 1975). The informal sector is particularly plagued by low back pain, MSDs, and severe injuries related to MMH. The informal sector accounts for about 30% of the Latin American working population and about 70% in some developing countries (Koplan, 1996).

A study of MSD symptom prevalence in the informal or unorganized sectors of West Bengal (Gangopadhyay et al., 2003) assessed 25 male workers from 5 contrasting occupations and found high point prevalence estimates that varied by occupation. Pain, numbness, swelling, and stiffness were significant issues faced by meat cutters, tailors, typists, visual display terminal operators, and weavers. Gangopadhyay et al. (2006), studying informal workers in sand core manufacturing, introduced a combination of work organization and engineering changes that reduced exposure to low back pain and increased productivity by up to 30%.

A random sample of 190 railway porters out of 500 porters at a railway station in Lucknow, Uttar Pradesh, India, was studied and compared with a group of 68 controls with similar socio-economic status (watchmen, 'peons') (Gupta and Ram, 1987). Data on back pain and other socio-economic risk factors were collected through a questionnaire. The prevalence of low back pain in the porters varied by age, from 59% in porters under 25 years old to 76.3% in porters aged 36–45 years, compared to 6.2% and 11.1% in the control group. Age, duration of work, and load carried out were statistically significant risk factors. Shockingly, the average load manually carried per porter per day ranged from 5 to 9 quintals (0.5 to 0.9 metric tons), with an average of 5 to 6 quintals per day. The study recommends ergonomic training, small trolleys, and push carts to replace manual lifting.

While numerous in vitro and in vivo studies are conducted under controlled laboratory conditions using various imaging techniques, few provide insights into the intersegmental lumbar spine behavior during everyday activities. Mörl et al. (2005) measured the intersegmental lumbar spine motions to recognize inter-subject differences during load lifting. Individual differences exist in intersegmental lumbar spine motion both at the participant level and across all lumbar levels. The lumbar spine's motion was also affected by the lifting technique. Lifting with bent knees significantly reduced the lumbar motion ranges in many subjects. They concluded that special instructions are advisable for reducing lumbar spinal motion. This understanding is vital for reducing spinal loading and preventing spinal disorders in MMH activities.

While most manual lifting in industries is performed on a smooth surface, manual lifting in outdoor environments involves surfaces that could be smoother or even. Studying the lifting biomechanics in these stressed conditions might provide insight into the probable mechanisms of the causes of lifting-related injuries (Jiang et al., 2005).

Findings suggest that lowering may pose a more significant hazard to the lower back than lifting. Research on back pain patients indicated that their overall lifting technique remained similar to that of control subjects; however, the activation patterns of paraspinal muscles differed. Findings suggest that to identify injuries in the lumbar region, extensive biomechanical analysis using EMG may be required (Larivière et al., 2002).

Role of Ergonomics in promoting sustainability

A sustainable workforce is essential as it safeguards employees' long-term health and well-being, enhancing productivity and reducing absenteeism linked to work-related health issues. Through a commitment to occupational health and safety, sustainable workforce strategies also bolster job satisfaction and retention, fostering a stable and motivated workforce crucial for sustained organizational success. Ergonomics can play a significant role in promoting sustainability among MMH workers in the unorganized sectors. Initially, it enables the assessment of MMH activities to identify health issues and their underlying causes. Subsequently, ergonomics facilitates the design of targeted interventions to mitigate these problems. By optimizing work processes, equipment design, and workplace environments to better suit physiological capabilities and minimize strain, ergonomics enhances worker health and safety and contributes to improved productivity and overall sustainability within these sectors.

There are three distinct approaches for assessing manual material handling (MMH) capabilities and establishing recommended workload limits (Sanders and McCormick, 1987):

1. Biomechanical Approach: This perspective considers the body as a system of links and joints. It uses physics principles to analyze the mechanical stresses on the body and the muscle forces required to counteract them.

2. Physiological Approach: This approach focuses on energy consumption and the stresses experienced by the cardiovascular system during manual material handling tasks.

3. Psychophysical Approach: This method evaluates how individuals perceive and respond to different workload conditions, incorporating subjective assessments of comfort and fatigue.

Wang et al. (1998) used the NIOSH lifting guide and studied low back pain and related risk factors. Their findings indicated that the lifting index is a reliable tool for evaluating the potential risk of low-back injury in MMH activities.

Over the past fifty years, various methods have been developed for assessing the risk factors of MSDs. Many of these techniques use only observational methods and are, therefore, easy to use and apply in different working conditions. These methods assess work postures and indicate overall postural risk severity. Using the findings from these techniques, policymakers or ergonomists can change work conditions, such as machine redesign or workplace layout redesign, to improve overall working conditions. Ovako Working Posture Analysis System (OWAS) (Karhu et al., 1977), Rapid Upper Limb Assessment (RULA) (McAtamney and Corlett, 1993), Quick Exposure Checklist (QEC) (Li and Buckle, 1998), and Rapid Entire Body Assessment (REBA) (Hignett and McAtamney, 2000) are a few of these observational techniques used in the field and industry setup.

Ergonomic Interventions to improve the health of MMH workers

Ergonomic interventions can be applied at different levels. At the activity level, interventions include engineering controls such as redesigned lifts. Interventions can also involve introducing safe lifting practices and using personal protective equipment at the work organization level. There is evidence in the literature that introducing appropriate interventions leads to a reduction in MSDs. Most of the workforce in any developing economy works in the informal sector, and studies on the introduction and efficacy of interventions in these countries are limited (Ketola et al., 2002; Putz-Anderson, 1988; Westlander et al., 1995).

Manual lifting techniques, including the size and shape of the load, have been extensively studied by researchers, and an association between lower back pain and MMH activity has been established. Worldwide, millions of people are affected by low back pain, which impacts their financial as well as mental health. Additionally, some tests use lifting in various settings to assess fitness for return-to-work conditions. Further studies should aim to understand the level of association between the risk factors and the prevalence of low back pain (Cole and Grimshaw, 2003).

Holmström and Ahlborg (2005) studied the effects of warming-up exercises in the morning on the stretchability of muscles, flexibility of joints, muscle strength, and endurance in construction workers. Results indicated a positive effect of morning exercise, with a significant increase in thoracic and lower back mobility and improved flexibility in the hamstring and thigh muscles. In contrast, the subjects in the control group showed a prominent reduction in the endurance of the back muscles. These results suggest that moderate warm-up exercises in the morning can improve joint and muscle flexibility and endurance.

The inclusion of rest allowances reduces the risk of injuries due to MMH. Taking timely rests during MMH activity relaxes muscles, reducing the risk of injury. Studies aimed at determining whether rest allowances could be established using psychophysical methods, as well as examining the effects of gender and handling frequency on work-rest schedules, found that total working time decreased. At the same time, total resting time also declined as handling frequency increased. High-frequency tasks necessitated more frequent rest allowances, and for the same manual handling tasks, women required more frequent and more extended rest periods than men (Genaidy and al-Rayes, 1993).

Movement assist devices are crucial for manual material handling (MMH) jobs, as they significantly reduce the musculoskeletal strain involved in completing tasks. However, studies have shown that these devices primarily minimize the gravitational forces of the task, while their added inertia can increase the dynamic manual requirements. As a result, subjects often exert high push and pull forces when using these devices. Additionally, experimental manipulations have only moderately affected the force levels observed during these tasks (Woldstad and Chaffin, 1994).

Conclusion

The unorganized sector is a dominant workplace in India and other developing countries, characterized by significant occupational health hazards such as Musculoskeletal Disorders (MSDs). Manual Material Handling (MMH) is a primary task within these sectors and is closely linked to developing MSDs. Research suggests that proper intervention helps to reduce many occupational hazards. Some intervention techniques include engineering controls, safer work practices, work organization modifications, training, and personal protective measures. In the organized setup, especially in developed countries, these interventions have been implemented and have proven helpful in preventing occupational health issues in most cases. However, it is hard to implement these interventions in developing countries since most of the workforce works in the informal sector. In conclusion, adopting an ergonomic approach helps improve workers' physical and mental health. These changes bring about sustainability within the organization by improving productivity and efficiency.

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Chapter- 18

Plankton act as a key indicator of the health and stability of aquatic ecosystems: A review

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Keywords: Bio-indicator, environment, plankton, water quality

Abstract:

Bio-indicators help keep track of how healthy our natural ecosystems are. Every living thing in a biological system gives clues about its environment. Plankton, which includes both phytoplankton and zooplankton, respond rapidly to environmental changes such as shifts in nutrient levels, temperature fluctuations, and pollution. It reacts quickly to changes in the environment. It is an important marker for checking water quality and indicates when water is polluted. Their sensitivity and central role in the aquatic food web make them invaluable for monitoring water quality and detecting ecological shifts. Researchers found a clear link between the ecosystem's living (biotic) and non-living (abiotic) parts. They also noted how helpful phytoplankton zooplankton are as bio-indicators for spotting how well aquatic areas are doing. Researchers gain insight into ecosystem conditions, potential stresses, and overall biodiversity by analyzing plankton diversity, abundance, and composition. Some plankton species can handle harsh conditions and even thrive in dirty water, showing a high tolerance. On the other hand, if sensitive species are missing, that area has low tolerance. So, using these organisms can improve our monitoring studies on water quality. This review highlights recent studies on plankton dynamics, explores their applications in environmental assessment, and discusses the implications for ecosystem management.

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Introduction:

In an aquatic ecosystem, life is closely related to water's Physical, Chemical, & Biological properties. All these factors play a significant role in controlling everything. So, to get a good grasp of aquatic life, we need to know both the organisms and their environment. Now, there is also a connection between different groups of organisms (*Patra and* Madhu, 2009; Dutta et al., 2014; Chakrabarti et al., 2024). For instance, producers like plants, and consumers like fish and other animals. The biodiversity here is truly unique. It ranges from tiny plankton—both phytoplankton & zooplankton—to larger creatures like fishes, amphibians, reptiles, & even some mammals (Polazzo et al., 2022; Roy et al., 2022; Biswas et al., 2023). Studying a variety of plankton and their roles helps us better understand the ecosystem's character and economy. There are these special species called bio-indicators. Their populations or functions can tell us a lot about the health of the environment (Pereira et al., 2022; Das et al., 2023). There are lots of different kinds of bio-indicators, like in Figure 1. Plankton, like microalgae, copepods and small water crustaceans, are a great example of these bio-indicator species. They can be monitored for biochemical, physiological, or behavioral changes in aquatic ecosystems. They also help us understand how pollutants build up in the aquatic ecosystem (Cuadro et al., 2022). Planktons are those little microbes floating along the water currents. Phytoplankton forms the base of the food chain since they act like energy converters in the water.

On the other hand, zooplankton plays a key role too. They link phytoplankton and fish together. These organisms are fantastic indicators of water quality and the ecosystem's overall health because they quickly respond to environmental changes (Stanley et al., 2016). In water bodies, plankton is responsible for much primary production. So, they are a group of organisms containing chlorophyll, including phytoplankton. These planktons form communities that cycle vital energy and then pass it up to higher trophic levels (Parmer et al., 2016). Studies have shown that the types of plankton and how often we see them can vary quite a bit across different water bodies. This depends on things like nutrient levels, shape of the area, age, and other factors. Because of this variation, we can use them to show how healthy lake ecosystems are (Negrete-García et al., 2022). Planktons respond fast to ecological changes in their surroundings. They are excellent indicators of water quality and trophic conditions because they reproduce quickly. When everything is natural and good for them, their presence within an ideal range is based on key abiotic factors like oxygen levels, temperature, and pH—and their relationships with other organisms. Plankton communities' shifts help determine the trophic state of water bodies (Rani et al., 2021). Bio-monitoring has become important lately for checking our water quality and studying pollution (Garg et al., 2021).

The following are some of the advantages of using Bioindicator:

1) Organic results can be decided.

2) Assists in monitoring the opposing and synergetic impacts of different contaminants on the environment.

3) Toxicology and the antagonistic impacts of poisons on plants and people can be observed early.

4) Due to their wealth, they can be effortlessly counted.

5) Compared to other specialized measuring frameworks, it is financially reasonable.

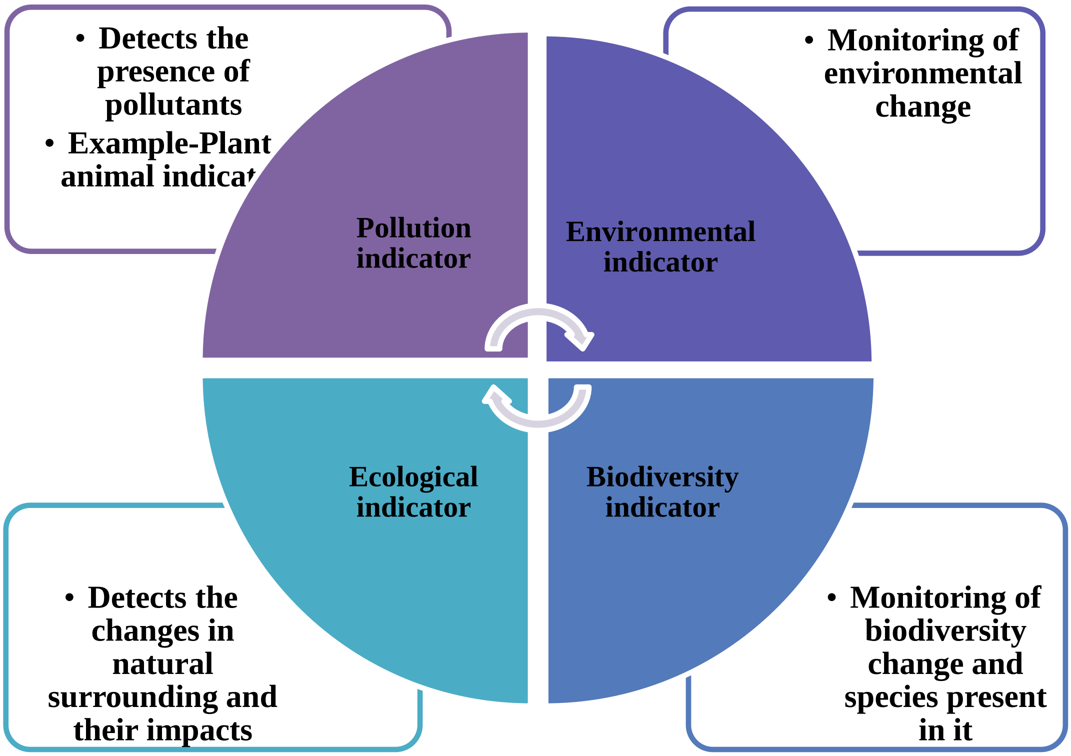

Figure 1. Types of Bio-indicator

Phytoplankton

Phytoplankton are pretty like other plants we see around us. They have chlorophyll and need sunlight to do photosynthesis. Most of them are active and can swim near the ocean's surface, where sunlight shines through the water (Verma et al., 2012; Singh and Ahluwalia, 2013). Photosynthesis helps them grow, and closely related to these two things are the use of food light plays a significant role. Though they comprise about 1% of all photosynthetic life on Earth, they produce around 50% of the global net primary production (Field et al., 1998). Phytoplankton, also called microalgae, are super sensitive to pollution. This sensitivity can show up in how many there are or how quickly they do photosynthesis. Some studies even suggest that algal assemblage could be used as an indicator of water quality. For instance, ten polluted tolerance algae species can handle pollution quite well. These include *Euglena viridis*, *Nitzschia palea*, *Scillatoria limosa*, *Scenedesmus quadricauda*, *Oscillatoria tenuis*, *Stigeoclonium tenue*, *Synedra ulna*, *Ankistrodesmus falcatus*, *Pandorina morum*, & *Oscillatoria chlorina* (Palmer, 1969). The life of these photosynthetic organisms depends on many factors—like how much stuff is available for them to eat, temperature changes, water mixing, and other environmental factors. Climate change may alter their types, seasonal patterns, and taxonomic composition. So, do we see changes in phytoplankton diversity? That could mean our waters might be getting polluted. Evidence applicable that plankton have been utilized for successful monitoring of water contamination has been summarized in Table 1 and Table 2, which show types of species and their habitat.

Table 1. Show water status and habitat of various phytoplankton species

Phytoplankton species	Habitat	Water status	References
Nitzschia palea	Flowing small stream (Nala)	Polluted	Bhatt et al. 2001
Synedra sp.			
Navicula cryptocephala			
Euglena acus	River	Eutrophic	Sampoorani et al. 2002
Euglena oxyuris			
Ulva lactuca	Bay	Sewage pollution	Wu et al.,2022
Oscillatoria sp.	Urban lakes	Eutrophic	Kumari et al. 2008
Ankistrodesmus sp.			
Frafellaria sp.			
Chlorococcum sp.			
Selenastrum sp.			
Lyngbya sp.			
Synedra sp.			
Merismopedia sp.			
Microcystis sp.			
Scenedesmus sp.			
Navicula sp.			
Phacus caudate	Water bodies	Polluted	Rai et al. 2008
Oedogonium capilliforme			
Euglena sp.			
Chlamydomonas globosa			
Scendesmus limorphus			
Ulothrix sp.			
Spirogyra sp.			
Nitzschia cuspidate			
Nitzschia palea			
Anabena sp.			
Microcystis sp.			
Aphanizamenon sp.			
Rivuloria sp.			

Coelastrum sp. *Oocystis* sp. *Scendesmus* sp. *Zygnema* sp. *Chlamydomonas* sp. *Chlorella* sp. *Spirogyra* sp. *Tribonema* sp. *Closterium* sp.	Reservoir	Polluted	Hulyal and Kaliwal, 2009
Ankistrodesmus falcatus *Oscillatoriabrevis* *Nitzschia palea* *Chlorella vulgaris* *Chlamydomonas* sp. *Closterium acerosum* *Euglena viridis* *Navicula cryptocephala* *Spirulina* sp. *Stigeoclonium tenue* *Synedra ulna*	River	Polysaprobic	Jindal and Sharma 2011
Microcystis aeruginosa, *Anabaena bergii*	Reservoir	Polluted	Katsiapi et al., 2011

Zooplankton

Zooplankton are tiny animals that live close to the surface of water. They're not very good at swimming though. These little creatures eat things like bacterioplankton, phytoplankton, and detritus. They are essential for fish and many other sea animals too since they provide a key food source. Now, it's interesting to note that zooplankton don't rely directly on nutrients to stay alive. However, their growth can change based on how much and what kind of algae, bacteria, & detritus there is in the water. They help the ecosystem by connecting primary producers (like plants) to higher trophic levels. The nano-phytoplankton is the dominant fraction in oligotrophic waters (those with low nutrient levels). This allows quick growth of zooplankton-like filter feeders such as calanoids & and large cladocerans, as shown in Table 1 (Xu et al. 2001). However, switching to eutrophic systems, where nutrients are plentiful, and small filter feeders like rotifers and tiny cladocerans (bosminids) have become very common (Table 1). These little creatures are more than just food; they also act as bio-indicators. This means they can help to monitor water pollution eutrophication and give hints about water quality in fresh bodies of water. To understand the health of a freshwater body, it's vital to look at seasonal changes in the zooplankton present. Different species and the variety of zooplankton biomass help determine the aquatic ecosystem's status. The potential for using zooplankton as bio-indicator species is high because their development relies on factors like abiotic ones (like saltiness, temperature layers, pollutants) and biotic factors (like availability of food or competition).

Table 2. Show water status and habitat of various Zooplankton species

Zooplankton species	Habitat	Water status	References
Moina sp.	Himalayan lake	Polluted	Jha and Barat, 2003
Daphnia sp.			
Bosmina sp.			
Cyclops sp.			
Phyllodiaptomus sp.			
Brachionus angularis	Lake	Eutrophic	Panikkar et al., 2022
Keratella cochlearis			
Brachionus quadridentatus			
Filinia longiseta			
Polyarthra vulgaris			
Trichocerca capucina			
Conochilus dossuarius			
Arcella vulgaris	Himalayan lakes	Eutrophic	Islam et al., 2022
Bosmina sp.			
Lecane luna			
Difflugia sp.			
Brachionus angularis			
Brachionus falcatus			
Brachionus terminalis			
Cephlodella gibba			
Keratella cochlearis			
Keratella tropica			
Chydorus sphaericus			
Daphnia pulex			
Diaphanosoma excisum			
Thermocyclops crassus			
Mesocyclops leuckarti			
Anuraeopsis fissa	Coastal lake	Eutrophic	Kruk et al., 2021
Diaphanosoma brachyurum			
Brachionus angularis			
Filinialongiseta			
Keratella cochlearis f. tecta			
Keratella quadrata			

Pompholyx sulcata			
Proales sp.			
Trichocerca pusilla			
Bosmina coregoni			
Bosmina longirostris			
Chydorus sphaericus			
Monostyla sp.	Parennial ponds	Eutrophic	Rajagopal et al. 2010b
Keratella sp.			
Lapadella sp.			
Leydigia sp.			
Moinodaphnia sp.			
Diaptomus sp.			
Diaphanosoma sp.			
Mesocyclopes sp.	Rain-fed lake	Eutrophic	Sharma et al. 2010
Brachionus forficula			
Brachionus calcyflorus			
Cyclidium glaucoma			
Cypris sp.			
Brachionus sp.			
Paramoecium caudatum			
Oxytricha ovalis			
Oxytricha oblongatus			
Holophyra simplex			
Keratella tropica			
Keratella procurva			
Neodiaptomus schmackari			
Mesocyclops leuckarti			
Mesocyclops hyalinus			
Aspidisca sp.	River	Polysaprobic	Jindal and Sharma 2011
Stylonychia sp.			
Bodo sp.			
Brachionus angularis			
Colpoda sp.			
Larvae of Chironomus sp.			
Eristalis tenax			
Daphnia pulex			
Mesocyclops sp.			
Tubifex tubifex			

Rotaria rotatoria			
Keratella sp.	Urban lakes	Eutrophic	Byeon et al., 2021
Brachionus sp.			
Moina sp.	River	Eutrophic	Ferdous and Muktadir, 2009
Ceriodaphnia sp.			

Impact of temperature change on plankton diversity

Temperature plays a significant role in how well organisms perform their tasks. It affects photosynthesis and respiration. In chilly polar seas, even low temperatures cannot prevent them from proliferating (Smith and Nelson, 1985). The most significant shifts in phytoplankton species usually come from changes in how warm or cool the water is (Diehl et al., 2002; Smol et al., 2005). When temperatures rise, phytoplankton grow faster and gather more biomass—especially when plenty of resources are available (Padilla-Gamino and Carpenter, 2007). However, temperature changes can have an even more significant effect on animals that rely on others for food, like herbivores. Warming could ramp up their eating habits more than the primary phytoplankton production. It might boost these animals' control over phytoplankton by making them graze more. Mixing events in the water mix up things like light and nutrients, essential for phytoplankton growth (Diehl et al., 2002; Salmaso, 2005). Meteorological factors are super important in how waters mix. Heat exchange and wind can make layers of water unstable and reduce mixing.

At the same time, turbulent energy input helps with mixing. So, a bit of a tug-of-war is going on (Wetzel, 2001). This battle leads to a yearly dance between summer stratification and winter mixing. Climate change can reduce the balance between stratification and mixing (Boyd and Doney, 2002). Turbulent diffusion and phytoplankton cells settling down are vital ways that non-motile cells move up and down in the water column. These processes can shift when there is a change in how long or strongly thermal stratification happens (Huisman et al., 2006). Smaller plankton are often advantageous if there is not much turbulence to stir everything up (Findlay et al., 2001; Huisman et al., 2004).

Impact of change in nutrients on plankton diversity

The nutrients that plankton need to grow depend significantly on how water mixes. When water layers become more stable, nutrients stop moving from deeper areas. This means nutrient-depleted conditions are becoming increasingly prevalent in the environment (Huisman et al., 2004). Different mixing patterns can influence which types of algae have the upper hand when competing for these nutrients. Some algae are good at holding their spot near the surface where light is best (Falkowski and Oliver, 2007). Mechanistic models show that if vertical mixing happens less, it could change the balance between buoyant cyanobacteria and those sinking phytoplankton in richer waters (Huisman et al., 2004). Greater hypolimnetic means more oxygen is used in the deeper parts of lakes and seas. This dramatically affects how nutrients cycle internally (Jankowski et al., 2006; Schaeffer et al., 2012). So, in simple terms, climate change might boost phosphorus levels while keeping certain areas without oxygen for more extended periods. Expanding runoff can alter the asset proportion in certain sorts of frameworks, depending on the geochemistry of the catchment, and consequently change phytoplankton species' competitive advantage. The export of nitrogen and dissolved organic carbon from the catchment through a Swedish subarctic lake was controlled by temperature, indicating that climate can affect the balance between phytoplankton and bacterial production (Jansson et al., 2010).

Impact of seasonal variation on planktons

Plankton blooms are common in seasonal aquatic habitats, powering the activities of various ecosystems and communities and providing an essential energy source for higher trophic levels (Winder and Cloern, 2010). Seasonal phytoplankton succession is a community phenomenon determined by the population dynamics of different primary producers and consumers. Individual species' life histories and physiological responses to the changing abiotic environment are drivers of blooms. Population feedbacks affect the timing and extent of blooms through resource dynamics and predator-prey interactions (Jager et al., 2008).

Fluctuations in water temperature and light availability typically drive spring plankton blooms. Spring phytoplankton blooms in deep systems coincide with the onset of the thermos-stratification, increasing the average light exposure of phytoplankton cells in the mixed surface layer. Species thrive under these conditions. Phytoplankton blooms are closely linked to external light conditions controlled by ice cover, cloud cover, or day length and can occur independently of temperature changes in shallow, well-mixed systems (Sommer and Lengfellner, 2008).

The timing and extent of seasonal plankton blooms are changing in response to climate change, as demonstrated in many studies (Straile, 2002; Edwards and Richardson, 2004), and are supported by dynamic models of pelagic producer-grazer systems (De Senerpont Domis et al., 2007). In many ecosystems, shifts in plankton spring phenology have been linked to climate, but later in the season, other factors, such as biotic interactions, often complicate the extraction of a strong climate signal. The timing of blooms has changed in the western Scheldt estuary, with an earlier bloom onset coinciding with increased temperatures over the past 30 years (Kromkamp and Van Engeland, 2009). In the Baltic Sea, a shift towards a warmer North Atlantic Oscillation (NAO) has caused stratification and an earlier onset of the spring bloom (Smayda et al., 2004; Alheit et al., 2005), as well as shifts in the timing of numerous phytoplankton taxa in the North Sea (Smayda et al., 2004; Alheit et al., 2005). Amid the warm NAO stage, a prior spring sprout was watched

over Central European lakes due to quickened early summer algal concealment due to quicker herbivore development in hotter water (Straile, 2002).

Table 3. Trophic status of Plankton

	Oligotrophic	Eutrophic
	Closterium pseudodianae	***Chlorella vulgaris***

Phytoplankton species	***Merismopedia elegans***	***Cyclotella* sp.**
	Peridinium inconspicuum	***Euglena oxyuris***
	Ceratium hirudinella	***Scenedesmus quadricauda***
	Dimorphococcus lunatus	***Ankistrodesmus falcatus***
	***Dinobryon* sp.**	***Closterium acerosum***
	***Euastrum* sp.**	***Cryptomonas erosa***
	***Gloeocapsa* sp.**	***Gomphonema gracile***
	Sorastrum spinulosum	***Melosira granulata***
	Strombomonas verrucosa	***Microcystis* sp.**
	Synura adamsii	***Navicula cryptocephala***
	Tetraedron minimum	***Synedra ulna***
Zooplankton species	***Euchlanis dialata***	***Alona pulchella***
	***Actinophrys* sp.**	***Aspidisca* sp.**
	Bosmina longirostris	***Asplanchana brightwelli***
	***Coleps* sp.**	***Brachionus angularis***
	Cyclops bicuspidatus	***Brachionus calyciflorus***
	***Daphnia* sp.**	***Chydorus* sp.**
	Keratella procurva	***Colpidium* sp.**
	***Notholca* sp.**	***Epistylis* sp.**
	Voritcella nebularia	***Eucyclops* sp.**
		***Glaucoma* sp.**
		***Stylonychia* sp.**
		Voritcella convallaria

Conclusion

All these studies revealed significant correlations between abiotic and biotic ecosystem components and the usefulness of phytoplankton and zooplankton as bio-indicators to detect the health and trophic status of aquatic environments. Some species can tolerate harsh abiotic conditions and thrive in polluted environments, indicating high tolerance, while sensitive species are absent, indicating low tolerance. The results may improve the use of these organisms in water quality monitoring studies.

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Chapter- 19

Duckweed: A Natural Solution for Wastewater Treatment

Kavita Ghosal

Keywords: Duckweeds, Wastewater management, heavy metals, *Lemna species*, Phytoremediation, application

Abstract:
Duckweeds (members of Lemnaceae) are a highly effective solution for wastewater treatment, known for their fast growth, efficient nutrient uptake, and adaptability to diverse environments. This review presented duckweed's role in purifying polluted wastewater by removing contaminants such as nitrogen, phosphorus, heavy metals and other pollutants. Through bioaccumulation and phytoremediation, duckweed significantly lowers Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and total dissolved solids (TDS). Its rapid biomass production also presents biofuel, feed, or biofertilizer opportunities. Duckweed further improves water clarity by reducing turbidity and suspended solids, offering a sustainable, cost-effective wastewater treatment option that supports environmental and resource conservation goals.

Introduction:

Duckweed, a small and rapidly growing aquatic plant, has garnered interest in recent years due to its capacity for wastewater treatment. Despite their diminutive size, duckweeds are among the most prevalent organisms in freshwater ecosystems, often forming dense mats on the water's surface (Godfrey and Wooten, 1979; Ziegler et al., 2023).

Lemna's capacity to absorb toxic compounds found in water makes it a great indicator plant for evaluating water quality. It gathers phosphate, nitrogen, heavy metals, and antibiotics (Krupka et al., 2021).

Duckweed, a member of the Lemnaceae family, is frequently considered an annoyance in ponds and lakes because it grows well in nutrient-rich settings. In light of this, they may extract heavy metals like copper (Zhao et al., 2015), chromium (Uysal, 2013), cadmium (Wang et al., 2022) and many more, as well as contaminants (particularly nitrogen and phosphorus) (Iqbal et al., 2019; Liu et al., 2016) from wastewater at a high rate. Due to this capacity, Duckweed has already been utilized to purify wastewater from swine, industry, and homes.

Therefore, its unique physiological characteristics make it an effective bioagent for cleansing wastewater and accumulating heavy metals, which has drawn considerable attention to environmental remediation.

Biological Features of Duckweed:

There are 37 duckweed species, a type of floating aquatic plant, in 5 genera (*Spirodela*) (Tippery and Les, 2020). Duckweed is abundantly spread around the world. Despite being

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flowering plants, most of the duckweed propagates asexually, dedicating nearly all of its energies to vegetative growth. It may therefore quadruple its biomass in two days and develop faster than the majority of other plants (Chen et al., 2018).

With an exceptionally rapid growth rate and foliar pigment properties resembling those of terrestrial perennials, duckweed displayed characteristics of both slow-growing evergreens and fast-growing annuals. Because it can grow in various light conditions, duckweed can succeed in environments with dynamic light cycles and quick expansion cycles (Stewart et al., 2021).

The high rate of *Lemna* multiplication has resulted in numerous prospective biotechnological implements, including biofuel (Yang, 2022), animal feed (Pagliuso et al., 2022; Sembada et al., 2024) and even human food production (Appenroth et al., 2018). This is why, in ecotoxicological studies, the duckweed is recommended (OECD, 2006) as a test organism.

Duckweed as a Natural Cleanser for surpassed nutrients:

Agricultural fertilizers are fundamental for preserving soil fertility and boosting crop yields. From 2011/2012 to 2023/2024, global demand for primary nutrient fertilizers—nitrogen (N), phosphorus pentoxide (P_2O_5), and potassium oxide (K_2O)—has grown significantly. Nitrogen remains the most in-demand, with 109.7 million metric tons used in 2022/2023 and 111.6 million metric tons forecasted for 2023/2024 as per the report presented by Statistica, 2024 (Statistica Research Department, 2024). These nutrients are essential for plant growth: nitrogen aids protein production (Anas et al., 2020; Frink et al., 1999), phosphorus supports root growth and participates in the generation of nucleic acids and different biomolecules and mediates signalling processes and resistance in abiotic stresses (Bechtaoui et al., 2021; Khan et al.,2023). The most prevalent inorganic cation is potassium (K), essential for overall plant growth (White and Karley, 2010). Numerous vital enzymes, including those involved in protein synthesis, sugar transport, N and C metabolism, and photosynthesis, are activated by K. It is crucial to developing improved yield and quality (Marschner, 2012; Oosterhuis et al., 2014).

Fertilizer demand has risen from 177.2 million metric tons in 2011/2012 to a projected 195.4 million metric tons in 2023/2024, reflecting its importance in global agriculture (Statistica, 2024). However, overuse can lead to environmental issues like nutrient runoff, pollution, and eutrophication (Chandini et al., 2019; Buda et al., 2015), underscoring the need for sustainable practices.

Crops probably absorb at most 40% of this total (Zhou and Borisjuk, 2019; Sylvester-Bradley and Kindred, 2009), with the remainder reaching freshwater reservoirs before entering the ocean. Ammonium, organic N and P are the primary pollutants found in aquaculture wastewater effluent (Cao and Wang, 2010).

Duckweed's ability to remove excess nutrients, particularly nitrogen and phosphorus, is one of its most well-documented features. High concentrations of these nutrients are common in agricultural runoff and domestic wastewater, where they contribute to eutrophication, leading to harmful algal blooms and oxygen depletion in aquatic systems (Zhou et al., 2023).

A recent study analyzed water quality in aquaculture waters at 64 random locations in the western delta region of Andhra Pradesh. Around 78% of the water samples collected from that area were classified as poor and unsafe for drinking or domestic use. The mean ammonia concentration was 0.15 mg/L, with 78% of samples exceeding the World Health Organization's (WHO) acceptable 0.5 mg/L limit. Ammonia levels ranged from 0.05 to 2.8 mg/L, highlighting significant concerns about toxicity in aquaculture waters (Nagaraju et al., 2023).

Duckweed's key advantage is that it withstands elevated levels of ammonium ions (NH_4^+), which are toxic to many plants, animals, and humans at elevated concentrations. Common duckweed (*Lemna minor*) has been shown to thrive at NH_4^+ levels as high as 84 mg/L. This ability to absorb and tolerate high NH_4^+ concentrations make duckweed ideal for treating wastewater from domestic, agricultural, and aquaculture sources, which often have high NH_4^+ due to urea breakdown and fertilizer runoff. Unlike most plants, duckweeds prefer NH_4^+ over nitrate (NO_3^-) as their nitrogen source, a trait first observed in *Landoltia punctata* (Tian et al., 2021) and later confirmed in several other duckweed species.

In China, a study shows that the initial concentrations of pollutants in the wastewater were 6.00 ± 0.09 mg/L TN (Total Nitrogen) and 0.56 ± 0.02 mg/L TP (Total Protein), worse than Grade V under the Chinese Surface Water Environment Quality Standard (CSWEQS). Pollutants were assessed every two days, and after 16 days, TN and TP levels in all four duckweed treatment systems dropped below 0.5 and 0.1 mg/L, respectively, improving the water to Grade II, suitable for protected drinking water sources. Duckweed removed over 70% of pollutants through uptake, alongside microbial conversion, sedimentation, and volatilization (Chen et al., 2018).

In India, this study evaluated the nutrient removal efficiency of *Lemna minor* (duckweed) in municipal, sewage, and seafood processing plant wastewaters at four dilutions: raw, 25%, 50%, and 75%. Duckweed was added at 0.6 kg/m², and water grade factors were measured weekly. The highest removal efficiency—96% NH_3-N—was observed in 25% dilution across all wastewater types. In municipal wastewater, *Lemna minor* removed NH_3, NO_2, NO_3, PO_4, BOD, and COD at rates of 96%, 98%, 98%, 96%, 79%, and 79%, respectively. This demonstrates duckweed's potential as a cost-effective natural tool for wastewater treatment, with reuse potential in agriculture and aquaculture (Selvarani et al., 2015). Before *Lemna minor* (duckweed) was introduced to cover at least 50% of the maturation ponds, baseline wastewater quality was measured weekly for three months in a study conducted in Zimbabwe. According to Zimbabwe's 2000 Waste and Effluent Disposal rules, the influent and effluent were evaluated monthly for bacteriological, physical, and chemical criteria. After five months, the emphasis switched to parameters over limits, such as turbidity, TDS, TSS, conductivity, BOD, iron, phosphates, nitrates, pH and turbidity. Most metrics showed significant reductions within allowable limits, although phosphates, BOD, COD, and turbidity still showed reductions of more than 60% (Dalu and Ndamba, 2003)

The ability of *Lemna minor* L. to lower sulfate and chloride in Biological Oxygen Treatment (BOT) effluent from a coke oven factory was the focus of this study, which investigated phytoremediation as an economical and environmentally beneficial way to remove toxins from wastewater. Physico-biochemical indices like pH, Total Dissolved Solids (TDS), Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD) and elemental concentrations were accounted for to assess the quality of the water. The findings showed that raising the pH enhanced the water quality. Duckweed demonstrated its phytoremediation capacity by removing 30% chloride, 16% sulfate, and 14% TDS from BOT wastewater. Furthermore, after 21 days, a maximum growth rate increase of 30% was noted, indicating that duckweed is a practical choice for treating coke oven plant wastewater (Saha et al., 2014).

Total dissolved inorganic nitrogen (T-DIN) levels of 20–50 mg/L in effluents were effectively reduced using 0.3–1.0 g/L of duckweed. *Spirodela polyrhiza* achieved the highest nitrogen removal rates (2.0–10.8 mg T-DIN/L/day) and biomass production (52.6–70.3 mg d.w./L/day) across municipal, swine, and anaerobic digestion effluents. Duckweed biomass from all effluents was used to produce ethanol and methane. *S. polyrhiza* and *Lemna punctata* exhibited greater ethanol (0.166–0.191 g/g-biomass) and methane (340–413 NL CH4/kg VS) production due to their higher carbon, starch content, and calorific values. So, it is a two-way benefit coming from the study (Toyama et al., 2017).

In a study (Zhao et al., 2014) adding a carrier had no notable impact on duckweed growth, composition, or the recovery of total nitrogen (TN), total phosphorus (TP), and CO2, nor on TP removal. However, it significantly increased the effectiveness of the elimination of TN and NH_4^+-N by 19.97% and 15.02%, respectively.

Considering morphological observations and 16S rRNA gene analysis, strain RWX31 was preliminarily identified as *Pseudomonas sp*. This strain is the first aerobic denitrifying bacteria, isolated from the rhizosphere of *Lemna minor* (duckweed) with the capability to reduce nitrate leaching. Bacterium RWX31 exhibited stable growth and efficient nitrogen removal, with a nitrate removal efficiency of 81.3% at an initial concentration of 140 mg/L NO_3-N. Under aerobic conditions, the maximum nitrate-N removal rates were 30.9 mg/L/h for nitrate, 24.3 mg/L/h for nitrite, and 11.5 mg/L/h for ammonium as sole nitrogen sources (Ying-Ru et al., 2013).

A thorough investigation of denitrifying bacteria linked to the duckweeds *Lemna minor* and *Spirodela polyrhiza* showed that particular fatty acid derivatives and stigmasterol—two essential constituents of duckweed cuticles—have an impact on the interactions between plants and microorganisms (Borisjuk et al., 2018). These substances activate the enzymes nitrate and nitrite reductases, which promote bacterial nitrogen metabolism. Furthermore, the chemical composition of duckweed root exudates was discovered to be influenced by the denitrifying rhizospheric bacterium *Pseudomonas sp.* RWX31, which specifically caused the release of stigmasterol. Consequently, stigmasterol changed the makeup of the rhizosphere's microbial community, which in turn encouraged the development of denitrifying bacteria (Lu et al., 2021; Lu et al., 2014).

Effective on herbicides, fungicides and weedicides:

As the demand for food rises and agriculture and aquaculture expands, large quantities of toxic agrochemicals like pesticides (Pathak et al., 2022; Tudi et al., 2021), herbicides (Ghazi et al., 2023; Barroso et al., 2023) and fungicides are produced and applied each year. Many of these chemicals enter aquatic environments untreated, putting immense strain on ecosystems. Herbicides frequently come into contact with aquatic organisms through multiple short-term pulses rather than prolonged exposure, making their ability to recover between exposures crucial in determining overall toxicity. The chosen organism must tolerate and metabolize the compounds at relevant concentrations for bioremediation. Most studies on duckweed's ability to absorb and tolerate agrochemicals have focused on *Lemna minor*.

Lemna minor (common duckweed) is widely used in environmental risk assessments. Studies have revealed that glyphosate accumulation in duckweed reduces growth, yield, chlorophyll and carotenoid synthesis, and PSII activity while increasing shikimic acid levels. Exposure to 20 µM of glyphosate also elevated ornithine decarboxylase activity fourfold and increased biogenic amines like tyramine and spermidine. Peroxidase and catalase activities peaked at 20 µM and 7 µM, respectively (Sikorski et al., 2019).

Prasertsup and Ariyakanon (Prasertsup and Ariyakanon, 2010) demonstrated that duckweed effectively removes chlorpyrifos (CPF) from water in laboratory greenhouse conditions, advocating its capacity for mitigating ecological risks coupled with the release of 14C-CPF-BR in aquatic environments. Additionally, another study (Li et al., 2018) identified 2–OH-TCP as the 14C-radioactivity absorbed by duckweed from water. The bio-concentration factor (BCF) for 14C-TCP in duckweed enhanced with prolonged exposures, indicating duckweed's ability to absorb and accumulate 2-OH-TCP, likely aided by its fine, long roots.

A study assessed the toxicity of the herbicides MCPA (an auxin-like growth inhibitor) and chloridazon (CHD, a PSII inhibitor), as well as their mixtures, on floating plants and planktonic algae. Using two-way ANOVA and Abbott's formula, the researchers found that MCPA and chloridazon showed an antagonistic interaction with *Lemna minor*, while their joint impact was additive for *Desmodesmus subspicatus* (Bisewska et al., 2012). Other agrochemicals also impact aquatic plants. For instance, a research team (Yilmaz et al., 2021) investigated the effects of the insecticide zeta-cypermethrin on duckweed growth and bioremediation. Low concentrations (150 µg/L) of zeta-cypermethrin boosted development, while greater concentrations (300–600 µg/L) were toxic. According to the initial concentration, *L. minor* removed between 35.4% and 95.9% of the insecticide. Another study demonstrated that *L. minor* effectively cleans water contaminated with terbuthylazine, with its efficiency enhanced by biostimulants like Megafol or safeners like benoxacor (Panfili et al., 2018).

L. minor has proven to be a highly effective macrophyte for phytoremediation organic pollutants (Walsh et al., 2024; Mohedano et al., 2012). In some cases, it outperformed traditional wastewater treatment facilities, achieving a 94.45% reduction in BOD and a 79.39% reduction in phosphate, compared to the 50% reduction achieved by primary and secondary treatments (Priya et al., 2011) Besides, *L. minor*'s ability to remove and metabolize 4-chloro-2-fluorophenol (4-Cl-2-FP) (Tront & Saunders, 2007) finding that over 95% of the compound was metabolized within 77 hours, with less than 10% remaining in the plant has been confirmed (Reinhold, 2007).

Research has also explored duckweed's remediation potential against various agrochemicals. When there held a comparative study regarding the remediation efficiency of three macrophytes (*L. minor*, *Elodea canadensis*, and *Cabomba aquatica*) exposed to two fungicides (dimethomorph and copper sulfate) and a herbicide (flazasulfuron). *L. minor* proved the most successful at removing pesticides, with copper sulfate and dimethomorph being more bioavailable to macrophytes than flazasulfuron (Dosnon-Olette et al., 2009). Further studies on two duckweeds including *L. minor* and *S. polyrhiza*, noticed that both species were 10 times more effective at removing dimethomorph and pyrimethanil than the other macrophytes tested, with dimethomorph showing a higher removal rate (Dosnon-Olette et al., 2010).

Additionally, much research has looked into how duckweed reacts to various insecticides, individually or in combination. These include metolachlor, atrazine, metribuzin, lactofen, linuron, monolinuron, diuron, 2,4-D, alachlor, paraquat, propanil, and others, focusing on their removal rates and the plant's sensitivity to these chemicals (Rice et al., 1997; Mitsou et al., 2005; Gatidou et al., 2014; Wang et al., 2016; Tagun & Boxall, 2018; Kostopoulou et al., 2019).

In some instances, *L. minor* is less effective than other species, such as *S. polyrhiza*, when exposed to the metazachlor herbicide (Muller et al., 2010). However, *L. minor* demonstrated better atrazine adaptation than *M. aquaticum* (Teodorovic et al., 2011). While *L. minor* often outperforms *S. polyrhiza*, the roots of its selected accumulation of agrochemicals remain unclear. The distribution of duckweed species may confer advantages, but further research is needed on its behavior with various agrochemicals. For example, the limited uptake of compounds like lactofen, isoproturon, and glyphosate calls for more detailed investigation.

Heavy metals:

Water polluted by contaminants like heavy metals has become a significant global environmental issue, posing severe risks to human health and aquatic ecosystems. The growth of urban areas, changes in the climate, and industry are the primary contributors to an upsurge in heavy metal pollution. Key sources encompass municipal and industrial wastewater, city runoff, landfill leachates, mining waste and natural events like volcanic eruptions, weathering, and rock erosion (Thakur et al., 2021; Das et al., 2022). Heavy metal ions are toxic, potentially carcinogenic, and capable of bioaccumulating in living organisms. Even at low exposure levels, damages occur in the lungs, nervous system, liver, stomach, skin, reproductive systems, and kidneys. In response, more research is being done on effective ways to remove heavy metals from wastewater. Nevertheless, while some approaches are practical, their high preparation and operational costs may limit widespread use (Aziz et al., 2023).

Among the many technologies developed to tackle this issue, phytoremediation is an eco-friendly and low-cost biotechnology solution.

One of the most hazardous heavy metals is copper (Cu), which is categorized as a trace element (Bha et al., 2022; Tchounwou et al., 2012). Cu typically originates in wastewater from sources such as instruments, electroplating, glass, metal, ceramics, and plumbing (Van Schaik and Reuter, 2014).

The release of hazardous heavy metal-containing industrial effluents has a harmful effect on aquatic ecosystems. It threatens the survival of organisms, which disrupts the food chain and poses risks to human health (Singh et al., 2022). Therefore, efficient methods for treating wastewater containing heavy metals are essential.

A study conducted showed the removal of copper (Cu) from contaminated water by two floating plant species, *Azolla filiculoides* and *L. minor*, was studied under varying Cu (II) concentrations (0.25–1.00 mg/L) and sampling times (Days 0, 1, 2, 5, and 7). Both species demonstrated the ability to remove Cu at a concentration of 1.00 mg Cu/L, with *A. filiculoides* achieving a 100% removal rate and *L. minor at* 74% by the fifth day. *L. minor* experienced both growth inhibition and morphological damage, including shrinkage of its internal structure, due to higher Cu accumulation in *L. minor* (2.86 mg/g) compared to *A. filiculoides* (1.49 mg/g) (Al-Baldawi et al., 2012).

Plant diversity is vital for ecosystem productivity and stability, but mechanisms behind resilience in harsh conditions are not fully understood. In another study examined how *Lemna aequinoctialis* and *Spirodela polyrhiza* respond to copper stress (1.0 mg/L) and low temperatures (5°C) when grown alone or together. At 25°C, both species grew similarly, but *L. aequinoctialis* grew 55.5% faster in co-culture with *S. polyrhiza* under high copper. *S. polyrhiza* accumulated more copper in cell walls, reducing copper toxicity for *L. aequinoctialis*. Low temperatures heightened copper toxicity, reducing growth and photosynthesis, but co-culture improved *L. aequinoctialis*'s growth and photosynthetic activity through metal compartmentalization and increased biomass (Shi et al., 2020).

Aquatic macrophytes can bioaccumulate toxic metals from wastewater, making them valuable for use in phytoremediation.

The bioaccumulation of four heavy metals—Cr, Cu, Pb, and Zn—in *Lemna gibba* (duckweed) was analyzed to assess its potential as an environmental indicator of contaminated industrial wastewater. A previous study (Hegazy et al.,2009) found that *L. gibba* bioaccumulated Zn most, followed by Cr, Pb, and Cu, with respective bioaccumulation factors of 13.9, 6.3, 5.5, and 2.5. Heavy metal buildup led to frond color changes from green to pale green and eventually degreened. As metal accumulation rose, chlorophyll a levels fell, chlorophyll b increased, and carotenoid content surpassed combined chlorophyll levels, especially in pale green fronds. Zinc had the most substantial negative impact on chlorophyll, while Cr and Cu correlated positively with carotenoids. This visible color change and high metal accumulation highlight *L. gibba*'s potential for phytoremediation and bioindication.

Lead (Pb) is one of the most hazardous environmental contaminants. A recent study evaluated *Lemna gibba* as a bioaccumulator and bioindicator of Pb pollution, studying its Pb re-release and pigmentation recovery over 12 days. Duckweed was exposed to PbCO3 (10–100 mg/L), with bioaccumulation, removal efficiency, and pigment recovery assessed every two days. At 10 mg/L, Pb removal efficiency reached ~50% after 12 days but decreased at higher Pb concentrations. The highest bioconcentration factor (BCF) was 943 mg/L at 10 mg/L Pb exposure. Pigment recovery was ~50% in plants exposed to 10–40 mg/L, indicating *L. gibba*'s potential as a Pb biosensor due to active Pb uptake (Hegazy et al.,2017).

The ability of *Lemna minor* to absorb Cr (VI) under ideal nutritional circumstances was investigated in this work. Over seven days, the plant's uptake of chromium was estimated at different amounts. *Lemna minor*, which was harvested every 24 hours for five days, shown no toxicity in a time-course experiment with 3 mg/L chromium. Atomic absorption spectroscopy was employed to assess the buildup of chromium. As chromium concentration rose, plant growth and chlorophyll content fell. The bio-concentration factor (BCF) declined with increasing doses, while the maximum absorption (5.8×10^3 μg/g) was attained at 8 mg/L. At 3 mg/L, the BCF was 1000. By the third day, growth and chromium accumulation had peaked (3119 μg/g), suggesting that *Lemna minor* is a potent chromium accumulator that can be exploited to remove Cr (VI) from waterways (Thayaparan et al., 2015).

Exposure to metal concentrations beyond physiological tolerance limits triggers antioxidant enzyme activity, as well as proline and organic acid synthesis in duckweeds, helping them mitigate metal toxicity. Metal tolerance among different duckweed species varies depending on environmental water conditions, including pH, temperature, electrical conductivity, and the types and concentrations of metals present. The concentration and duration of exposure primarily influence duckweed's metal uptake and bioaccumulation potential (Ali et al., 2015).

Recent research (Rezania et al., 2016; Mustafa and Hayder, 2020) found that among four species of free-floating macrophytes—*Pistia stratiotes*, *Eicchornia spp*., *Lemna spp*., and *Salvinia spp*.—*Pistia stratiotes* demonstrated the highest potential for phytoaccumulation. Similarly, another study (Badr El-Din and Abdel-Aziz, 2018) established that aquatic plants such as duckweed, water hyacinth, and green algae effectively reduced water quality indicators in wastewater to levels suitable for irrigation. In this study, duckweed outperformed water hyacinth and green algae in nutrient uptake. Additionally, it has been concluded effluent treatment plants (ETP) that use biological methods over chemical methods are preferred due to lower inorganic sludge production, reduced operating costs, and the complete mineralization/stabilization of dyes through biological processes

In a study using a 3:1:18 mix of textile, distillery, and domestic wastewater, *Lemna minor* and *Azolla filiculoides* treated the water over 28 days (Holkar et al., 2016). Both macrophytes met reuse and discharge limits for electric conduction, total dissolved solids, heavy metals, pH and sulfate. *A. filiculoides* removed 96% of chemical oxygen demand, slightly higher than *L. minor* (92%), while *L. minor* achieved greater biochemical oxygen demand removal (92% vs. 90%). Phosphorus, nitrogen, and fecal coliforms exceeded limits, with counts of 400 for *L. minor* and 267 for *A. filiculoides*. Both plants significantly improved wastewater quality compared to the control (Amare et al., 2018).

In another study, it assessed the toxic and genotoxic effects of surface water samples on duckweed using growth parameters and biomarkers like pigment content, peroxidase activity, lipid peroxidation, and alkaline comet assay. Water samples were brought monthly for three months from three sites along the Sava River and its confluent (Croatia), with physicochemical tests measuring conductivity, oxygen demand, suspended solids, nitrates, and other nutrients. Surface water samples reduced duckweed growth, chlorophyll, carotenoids, and peroxidase activity, increasing lipid and DNA damage, especially from industrial wastewater. The results highlight duckweed's sensitivity and value as a water quality indicator (Radić et al., 2011).

Although microplastics (1–1000 µm) are ubiquitous in many settings, their impact on freshwater plants is not well understood. According to this study, on the surface of *Lemna minor*, 10–45 µm polyethylene microplastics adsorb at concentrations of up to 7 particles/mm2, yet they had no influence on growth or photosynthesis after seven days. However, because the freshwater amphipod *Gammarus duebeni* consumed microplastics by feeding on contaminated *L. minor*, with no immediate consequences on mortality or mobility, *L. minor* may spread microplastics along the food chain. This emphasizes the role of trophic transmission and plant adsorption in the environmental fate of microplastics (Mateos-Cárdenas et al., 2019; Das et al., 2023).

The impacts and adherence of two natural particles (cellulose and wood dust) and three types of microplastics (polyethene microbeads, tyre wear particles, and polyethene terephthalate fibres) on *L. minor* were investigated in this study. The findings indicated that microbeads and tyre wear particles considerably shortened the root length of duckweed and fibres, and natural particles and did not affect the plant's growth rate, chlorophyll content, or root length. Specific adhesion was demonstrated by the ten-fold higher rate of attachment of polyethylene microbeads to duckweed compared to other particles. Duckweed may be useful for biomonitoring microplastic pollution because polyethylene microplastics are common in freshwater (Rozman and Kalčíková, 2022).

Technological innovations and metal extraction:

This study lays the groundwork for using ionic liquids (ILs) to pretreat duckweed biomass, leveraging its properties for efficient metal removal (Sekomo et al., 2012), starch accumulation (Cui et al., 2011) and protein recovery. Two ILs, dimethyl ethanol ammonium formate ([DMEtA][HCOO]) and N, N-dimethyl butyl ammonium hydrogen sulfate ([DMBA][HSO_4]), were tested on *Spirodela polyrhiza* and *Lemna minor* for starch recovery (Xu et al., 2011), sugar release, protein recovery, and metal extraction. [DMEtA][HCOO] achieved near-complete starch recovery at 120°C, while [DMBA][HSO4] performed similarly at 90°C, both within 2 hours. Saccharification yields surpassed 90% after 8 hours, outperforming traditional biomasses. Protein solubilization was 50% in [DMEtA][HCOO] and 80% in [DMBA][HSO_4], though the low molecular weight of solubilized protein prevented recovery. [DMEtA][HCOO] was more effective for metal extraction, removing 81% of nickel from *Lemna minor*, compared to 28% with [DMBA][HSO_4]. Further optimization is needed for simultaneous metal extraction using ILs (Firth et al., 2024).

The latest study (Rai et al., 2024) gave an account of the eco-sustainable use of duckweed (*Landoltia* and *Lemna*) for phytoremediation of metallic contaminants in wastewater. Duckweed bioreactors primarily rely on phytoextraction and rhizofiltration, influenced by physico-chemical factors and plant-microbe interactions. Gene manipulation could enhance this process. The high starch and protein content of metal-contaminated duckweed makes it a valuable feedstock for biorefineries, supporting bioenergy (Xu et al., 2012; Chen et al., 2012), value-added products, and biofertilizers. Integrating duckweed-based phytoremediation with biorefineries can promote a circular economy and contribute to Sustainable Development Goals (SDGs).

Future outlook of duckweeds as a wastewater-manager:

Owing to their high nutrient intake, resilience in a variety of environments, and quick development, duckweeds—especially *Lemna* species—hold great potential for the treatment of wastewater in the future.

Duckweed absorbs phosphorus as phosphate ions and nitrogen as nitrate and ammonium ions during wastewater treatment. It works just as well as traditional therapy techniques, and in certain situations, better.

In addition to efficiently removing heavy metals, organic contaminants, and even certain microplastics from wastewater, these aquatic floras are likewise capable of absorbing nutrients like phosphate and nitrogen. Duckweed lowers these contaminants to levels that can considerably lessen their detrimental effects on aquatic habitats through nutrient uptake and accumulation.

Future studies aim to improve duckweed species and growing conditions for increased biomass output, pollutant uptake, and wastewater type adaptation. Furthermore, duckweed can flourish in various environments and be used in various water systems, including municipal wastewater and industrial effluents.

The environmental and financial advantages of collected duckweed biomass can also be increased by using it to make biofuel, animal feed, or biofertilizer. Incorporating duckweed systems into wastewater treatment plants is a sustainable and affordable way to enhance water quality and promote circular economy goals.

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Chapter- 20

Evaluation of frequently used water quality indices (WQIs) depending on their effectiveness in measuring river pollution: A case study on River Churni, West Bengal

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Keywords: Water quality Parameters, index, pollution, River Churni, monitoring

Abstract:

Water quality is highly dynamic attribute of any water body that varies depending on time and space. It is a complex measurable character calculated based on various water quality parameters. The parameters maybe physical parameters (Colour, temperature, turbidity, odour etc.), chemical parameters (pH, hardness, alkalinity, chloride, phosphate, nitrates etc.), and biological parameters (nutrient, virus and microorganisms). Individually, these parameters are not adequate to provide clear idea about water quality of any water body thus, a reporting tool of water quality is very much needed to consolidate the impact of all parameters into a single number. Water quality index (WQI) does the same job. Many researchers have used several WQIs to validate the researches but these indices differ in their effectiveness as well as in construction procedure. The main objective of the present study is to evaluate the usefulness of some frequently used WQIs in measuring the pollution level of a river. River Churni, a river of Nadia district of a West Bengal is selected for the case study. Our findings suggest that water quality index given by Canadian council of ministers of the environment (CCMEWQI) is the most valuable mathematical tool with high potentiality and flexibility having highest power of interpretation of pollution level in a river. This finding may be useful to many researchers and stakeholders for monitoring and testing the water quality of any river over the time.

Introduction:

Water is very crucial component for living on this planet and also for the sustainability of the environment. However, groundwater and surface water quality have long been deteriorating due to various natural and anthropogenic activities (Fortes et al., 2023). Water quality is highly dynamic to study and cannot be quantified using one or two parameters. A set of physical, chemical and biological parameters should be checked to determine the quality of water (Santra et al., 2003; Boyacioglu, 2007, 2010; Panigrahi et al., 2015; Bhattacharya et al., 2016; Mukate et al., 2019; Chakraborty et al., 2019). Measuring each of these parameters requires high knowledge of their interrelationship and interdependence with other external conditions (Iticescu et al., 2019). Theoretically, reports of water quality parameters need to be presented in such a manner that can be understood by various stakeholders engaged in water quality

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evaluation, assessment and monitoring. Water quality indices (WQIs) have been found to be efficient strategy for collecting information with aggregation of many indicators or water quality parameters which could be difficult to interpret separately (Fortes et al., 2023). WQIs help to translate technical facts facilitating overall water quality reporting and interpretation despite the fact that this indices provide a preliminary view of water quality, they have limitations associated to their modeling method, together with information loss due to aggregation and subjectivity inherent to the parameter (Abtahi et al., 2015; Boyacioglu, 2010; Hurley et al., 2012; Rickwood and Carr, 2009). WQIs are mathematical tools or formulations that enable the aggregation and conversion of a experimental dataset with selected water quality parameters into a dimensionless single value (Akter et al., 2016; Brown, 1972; Hurley et al., 2012; Lumb et al., 2011; Mukate et al., 2019).

River Churni, an important source of the surface water of district Nadia of West Bengal (India), is an important tributary of river Bhagirathi- Hooghly. According to Das and Chakrabarty (2007), approximately two-thirds of the total fish species appeared to have been eliminated from this river since 1983 due to the huge pollution load. Besides several local source of pollutions, the river ecology mainly gets disturbed by the effluent of the sugarcane mill complex of Darshana (Bangladesh) several times throughout the year making its water very much polluted (Bakshi et al., 2016; Panigrahi and Bakshi 2016; Bakshi and Panigrahi 2015; Panigrahi et al. 2015; Sarkar and Islam 2019; Roy et al., 2022). The main objective of the study was to evaluate the water quality index of the river water using different water quality indices (WQIs). On the other hand, the present study was also aimed to identify the suitable water quality index among the commonly used indices to evaluate their benefits and limitations based on SOWT analysis (analysis of strengths, weaknesses, opportunities and threats). The result obtained from this investigation will surely be helpful to the future researchers in applying WQI in River Churni and other similar streams.

Materials and methods

The study area and data sources

The investigation was carried out for 12 months and started with data collection in March 2022 and ended in February 2023. River Churni is one of the major distributaries of river Mathabhanga. The river originates at Pabakhali village (Majhdia) of Nadia District. It pours its content into River Bhagirathi-Hooghly near Shibpur (Nadia). Three sampling sites are selected throughout the stretch of river Churni (Table 1) in such a manner that S-1, S-2 and S-3 sites are situated at the upper, middle and lower stretch respectively. Sampling and evaluation of water quality parameters are done according to APHA (1995) guidelines. Dissolved Oxygen, Total Solid, pH and Electrical conductivity have been evaluated using digital meters at the sampling site. Data have been collected from each sampling sites four times a year *i.e.*, pre-monsoon, monsoon, post monsoon and winter. Three commonly used water quality indices have been incorporated to evaluate the water quality of river Churni. The selected water quality indices are The National Sanitation Foundation Water Quality Index (NSF WQI), the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI), Oregon Water Quality Index (OWQI).

Table 1. Sampling sites name and details.

Sampling Site	Latitude	Longitude	Site Code
Krishnaganj	23.403965ºN	88.709667ºE	S-1
Ranaghat	23.263231 ºN	88.6008545ºE	S-2
Aranghata	23.177679ºN	88.558168ºE	S-3

To evaluate the three selected water quality indices on the basis of their strengths, weaknesses, opportunities and threats, SWOT analysis is applied. Data regarding this have been collected, from science research journals of repute, published reports from renowned national or international agencies and doctoral thesis. Weight has been given to the reproducible articles, indexed in journal database like Scopus, Pubmed, Copernicus etc to make the evaluation utmost consolidated and extensive.

Selected parameters for different WQIs

For the calculation of NSF WQI, 9 parameters are incorporated viz., DO, BOD, pH, turbidity, total solids, Water temperature, nitrate total Phosphorus and fecal coliform. Each parameter is meticulously weighted depending on the magnitude of its importance on water quality following the classification by Brown et al. (1970). The Canadian Council of Ministers of the Environment Water Quality Index Model (CCMEW QI) was developed in Canada in 2001 (Fortes et al. 2023). The parameters used in calculating th e CCME-WQI values are not adjusted, allowing for easy use of water quality. In this study, pH, water temperature, Electrical conductivity, DO, BOD, nitrate, phosphate, total solid and fecal coliform are taken into consideration. To evaluate OWQI, the selected water quality parameters are as follows: water temperature, Electrical conductivity, DO, BOD, ammonia and nitrate, total phosphate, total solid and fecal coliform (Table 2).

Table 2. Parameters used to calculate index and their units

Sl. No.	NSF-WQI	CCME-WQI	OWQI
1.	pH	pH	Water Temperature (ºC)
2.	Water Temperature (ºC)	Water Temperature (ºC)	Electrical Conductivity
3.	Turbidity (NTU)	Electrical Conductivity(µS/cm)	DO (ppm)
4.	DO (ppm)	DO (ppm)	BOD (ppm)
5.	BOD (ppm)	BOD (ppm)	Ammonia and Nitrate (ppm)
6.	Nitrate (ppm)	Nitrate (ppm)	Total Phosphate (ppm)
7.	Total Phosphate (ppm)	Total Phosphate (ppm)	Total Solid (ppm)
8.	Total Solid (ppm)	Total Solid (ppm)	Fecal Coliform (MPN/L)

9.	Fecal Coliform (MPN/L)	Fecal Coliform (MPN/L)	

WQI assessment methods

The first water quality index has been developed by Horton in 1965 in USA using 10 water quality parameters (Akter et al., 2016). Among these 10 water quality parameters temperature and pollution level have been treated as adjustment factor and other eight selected parameters are pH, dissolved oxygen, total coliform count, total carbon, alkalinity, chloride and sewage treatment percentage (Lumb et al., 2011; Sarkar and Abbasi, 2006). The NSF WQI has been proposed by Brown (1970) from the National Sanitation Foundation or NSF as a modification of Horton Water Quality Index or HQI. The calculating formula of NSF WQI is as follows.

$$WQI = \sum_{i=1}^{n} Q_i W_i$$

Here Q_i is the sub index value for i-th parameter whereas W_i is the weight of that water quality parameter. Here, 'n' stands for number of evaluated water quality parameters.

Based on individual weight established by Sutandian et al. (2016) and Brown (1970) the weight used for each parameter are as follows: DO (0.17), Fecal Coliform (0.15), pH (0.12), Biological Oxygen Demand or BOD (0.10), Nitrates (0.10), Phosphates (0.10), Water temperature (0.10), Turbidity (0.08) and Total dissolved Solid (0.08).

The Canadian Council of ministers of the environment model of water quality index (CCME-WQI) happen developed in Canada in 2001 (Fortes et al. 2023). The parameters used to calculate the CCME-WQI value are not fixed as it allows flexibility regarding the adoption of water quality parameters. However, a minimum of four water quality parameters must be incorporated to determine the value. The calculation formula is as follows:

$$CCME\ WQI = 100 - \frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732}$$

The above mentioned formula have three major components *viz.*, F_1,F_2 and F_3. Here, F_1 is the percentage of the total selected parameters that do not meet the standard value (or BIS value). Whereas, F_2 is the percentage of the performed tests that do not meet the standard value. The calculation of F_1 and F_2 are as follows:

$$F_1 = \frac{Number\ of\ failed\ parameters}{Total\ number\ of\ parameters} \times 100$$

$$F_2 = \frac{Number\ of\ failed\ tests}{Total\ number\ of\ tests} \times 100$$

F_3, the amount of relativity by which the test values fail to meet the standard value, is calculated following the equation.

$$F_3 = \frac{nse}{(0.01 \times nse + 0.01)}$$

Here, *nse* stands for the collective amount by which the test values fail to meet the standard value. The *nse* value can be calculated by the incorporation of excursion value. Here, excursion value means the number of times the individual tests failed to meet the standard value. The formula for calculating *nse* and excursion are as follows:

$$nse = \frac{\sum_{i=1}^{n} excursion_i}{total\ number\ of\ tests}$$

$$excursion_i = \left(\frac{Failed\ test\ value}{water\ quality\ standard\ of\ the\ i^{th}\ parameter}\right) - 1$$

The calculation of OWQI or Oregon water quality index can be done by incorporating 8 selected parameters, i.e., pH, water temperature, DO, BOD, total solid, ammonia and nitrate, total phosphate and faecal coliform. Each parameter is meticulously weighted equally because unequal waiting is only appropriate for the assessment of WQI developed in a particular manner. The determination of sub-indices value for each parameter is done on the basis of the equations established by Cude (2001). The formula for calculating OWQI value is given below.

$$OWQI = \sqrt{\frac{n}{\sum_{i=1}^{n} \frac{1}{(Q_i)^2}}}$$

Here, Q_i stands for the sub index value for the i-th water quality parameter. And 'n' is the number of investigated water quality parameters.

The water quality status qualification (given in table 3) have been incorporated according to the classification developed by Sutandian et al. (2016) and Dunnate (1979). The interpretation of different WQI values can be useful to understand the qualitative status of water at the three sampling sites.

Table 3. Water quality qualification depends upon index value.

NSF WQI		CCME WQI		OWQI	
Index Value Range	Quality Status	Index Value Range	Quality Status	Index Value Range	Quality Status
91-100	Very Good	95-100	Very Good	90-100	Very Good
71-90	Good	80-94	Good	85-89	Good
51-70	Fair	60-79	Fair	80-84	Fair
26-50	Bad	45-59	Marginal	60-79	Bad
0-25	Very Bad	0-44	Bad	0-59	Very Bad

Determination of most fitted WQI for River Churni

To determine the best fitted WQI model to evaluate the overall pollution status of River Churni, West Bengal, the logical structure of SWOT analysis is applied. SWOT analysis is performed to strategically evaluate the WQIs. The analysis provides the possibility of determining and evaluating the interrelationship between the strengths, weaknesses, threats and opportunities of certain subjects. The analysis comprises two dimensions, viz., external and internal. The internal component comprises the strengths and weaknesses of the subject, whereas the external component comprises the opportunities and threats of the particular subject (Fortes et al., 2023).

Result and Discussion

River Churni and its pollution load

River Churni, an important river of the Nadia district of West Bengal (India), provides livelihood for a huge number of fishermen in the four blocks of Nadia district (Krishnaganj, Hanskhali, Ranaghat I and Ranaghat II). The river originates as a distributary of river Mathabhanga near Krishnaganj. After flowing about 54 kms the river pours its content into the river Bhagirathi Hooghly near Shibpur, Nadia. The river has been facing the problem of ecological degradation since the 1980s (Das and Chakrabarty, 2007; Panigrahi et al., 2015) mainly due to the effluent of sugar mill factories and wine factories situated at Darshana (Bangladesh). A huge number of fish species, plankton groups, and macrobenthic invertebrates have been reported to be eliminated from the river in the last few decades (Bakshi and Panigrahi, 2015). There are two main types of pollution sources: point sources and non-point sources. The point sources of the pollution are the sugarcane mill of Bangladesh, the wine factory of Bangladesh, municipal sewage from Birnagar and Ranaghat municipality, thread dyeing houses of Ranaghat, etc. Whereas the non-point sources are brick kilns, agricultural lands, jute retting, etc., situated at various places on both sides of the river.

Water quality of the river is receiving pollutants from various sources throughout the stretch. The effluent from sugarcane mill complex lowers the dissolved oxygen value, alters pH, increases BOD value. The prominent impact of this effluent is majorly noticed in the upper stretch. Whereas in the middle and lower stretches of the river, water quality remained disturbed for a few days. Regular tidal flow in the lower and middle part of the stretch minimize the effect of the pollutant very quickly. The major pollution sources of middle and lower part of the river are municipal wastes increasing the contamination of fecal Coliform in the water. Electrical conductivity remains high in the lower part of the river due to the dumping of solid wastes and brick kilns. The level of dissolved oxygen is very low throughout the stretch, whereas BOD values range high throughout the stream. The average and standard deviation values are given in Table 4 for all the evaluated parameters.

Application of different WQI methods to calculate the quality of the water

Different water quality parameters show that the river water remains better in the monsoon period. The higher rainfall could cause a better condition of river water quality because it dilute the pollutant naturally. The result of the WQI assessment shows that water quality is better at the lowest rate of the river regardless of the method applied. In all three calculation methods it is shown that the river water quality is either poor or very poor quality. The data of WQI is obtained sampling site wise. Though calculation of NSF-WQI can be done seasonally or monthly. DO, BOD, pH, turbidity, total solids, Water temperature, nitrate total Phosphorus and fecal coliform are assessed seasonally and meticulously weighted according to Sutandian et al (2016). The value of NSF-WQI ranges from 41.2 to 46.9 which means that overall pollution level of each sampling site is 'Bad'.

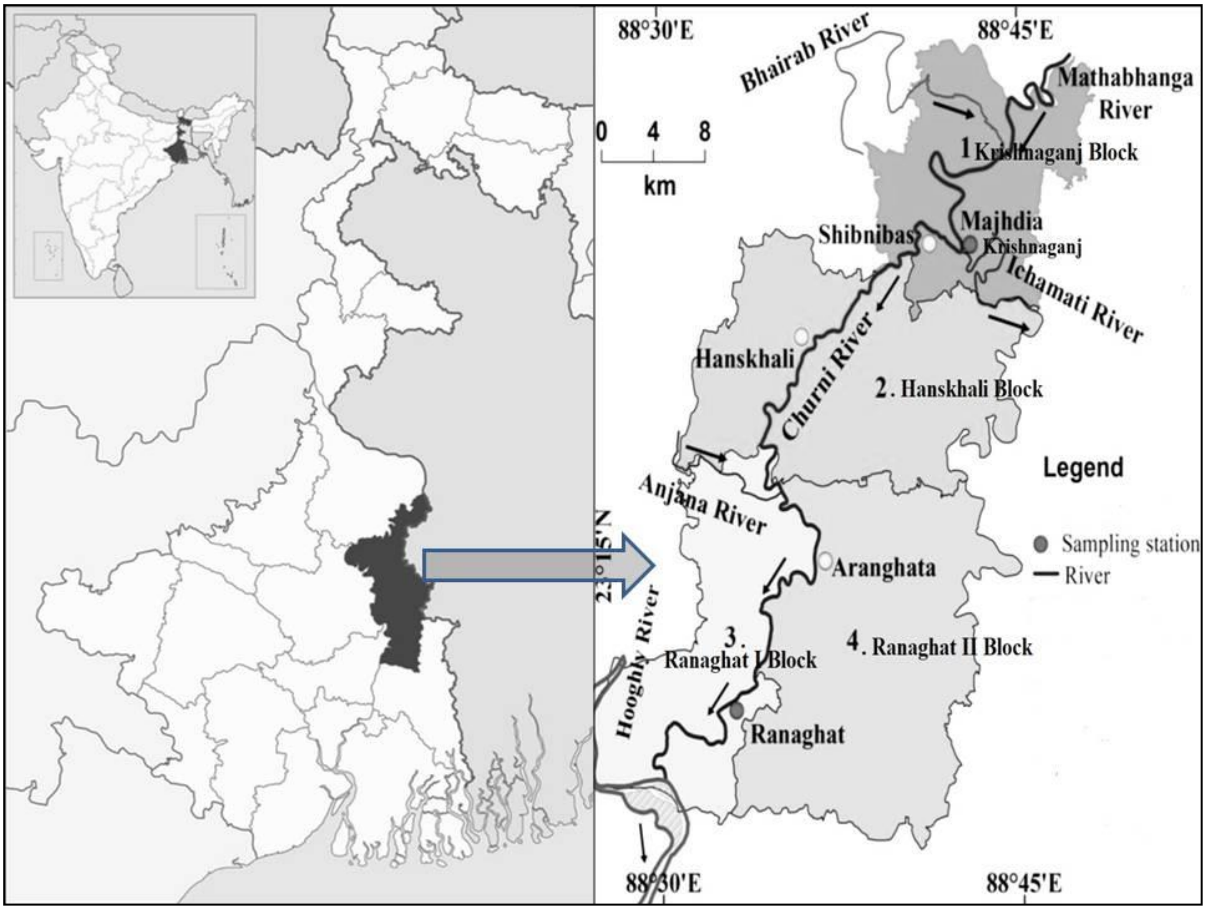

Figure 1. River Churni and position of sampling sites.

Table 4. Water quality Parameters of different sampling sites.

Sites	Values	Temp(°C)	pH	Turbidity (NTU)	DO (ppm)	BOD (ppm)	Nitrate (ppm)	Total Phosphate (ppm)	Total Solid (ppm)	Fecal Coliform (MPN/100 ml)	EC (µS/cm)
S-1	Avg	17.397	3.8660 2	4.52548	1.87842	4.38389	0.90066	0.2863	410.184	43648.5	342.408
	SD	12.2	3.8953	4.0876	1.28	3.31	0.159	0.14879	335.71	11956.2	115.

		107	2	6	029	618	23		1		718
S-2	Avg	27.8875	7.075	7.74167	2.575	8.1375	0.975	0.3675	649.695	34362.5	421.75
	SD	6.47178	0.49917	1.02477	0.9535	1.94567	0.67777	0.15327	100.686	33261.5	241.432
S-3	Avg	28.05	7.4	8.375	3.325	6.185	1.045	0.455	747.255	58025	461.5
	SD	7.1789	0.4899	0.96047	0.66018	1.26737	0.90486	0.16941	143.099	48944.9	244.951

The CCME WQI assessment is done using 8 parameters excluding water temperature as no standard values have been found for this parameter. The number of field parameter in S-1 is 6. Number of tests is 32 among which 19 tests fail to meet up the standard value. F1 and F2value for sampling site 1 (S-1) and sampling site 2 (S-2) remain same because the number of failed parameters number of taste and number of failed tests are equal for both sampling sites (Table 5).

Table 5. Calculated values of different components of CCME WQI

Sites	No. of Parameters	No. of failed parameters	No. of Tests	No. of Failed Tests	F1	F2	F3	CCME WQI
S-1	8 (excluding Water Temperature)	6	32	19	75	59.375	97.4337	21.16542
S-2	8(excluding Water Temperature)	6	32	19	75	59.375	98.3342	20.79329
S-3	8 (excluding Water Temperature)	4	32	13	50	40.625	99.7208	31.45452

Various research have been performed to confirm the contradiction visible when the usage of unique WQIs. In truth, the end result can be explained by using aggregation of the indices. but, the unparalleled of the water parameters varies in step with the spatio-temporal dimensions of its direction all through the cycle and in line with allocations and makes use of. The latter determines the selection of water excellent variables, the analytical approach, and the sampling period (Kachroud et al. 2019).

Table 6. Values of different WQIs and interpretation

NSF WQI		CCME-WQI		OWQI	
Index Value	Quality of water	Index Value	Quality of water	Index Value	Quality of water
41.2	Bad	21.16542	Bad	11.51	Very Bad
44.97	Bad	20.79329	Bad	11.43	Very Bad
46.9	Bad	31.45452	Bad	11.17	Very Bad

SWOT analysis to evaluate the best fitted WQI method

According to Sarkar and Abbasi (2006), selection of large number of parameters poses weakness because greater number of aggregated data leads to greater loss of information confirming inaccurate calculation of water quality index. But in case of river Churni the pollution sources are diffused. So, incorporation of incorporation of multiple water parameter is recommended. According to Nabizadeb et al. (2013), weighting of the water quality parameters is considered to be subjective allowing another weakness. To be very precise, weighting of water quality parameters is highly dependent on users' expertise and judgement (Dash and Kalamdhad 2021). So, we selected CCME-WQI for assessment of water quality of river Churni. Though, NSF-WQI is a very good reporting tool but due to average measurability and low flexibility it is not treated as the most appropriate WQI assessment method (Table 7). OWQI is is very strict in selection of parameters and with low flexibility. The weighting method is also ambiguous, thus it is not the ideal tool to evaluate the pollution level of river Churni.

Table 7. SWOT analysis and interpretation on the basis of River Churni

WQI methods	SWOT analysis				Remark on the basis of Churni River
	Internal forces		External forces		
	Strengths (+)	Weaknesses (-)	Opportunities (+)	Threats (-)	
NSF-WQI	Good reporting tool. Spatio-temporal comparison can be assessed easily.	Limited use of parameters. Chances of eclipsing (weighted geometric and arithmetic mean subject to over – estimation of quality) is	Recommended by many researchers for assessing overall water quality with special reference to drinking purpose. Data aggregation model	Absence of monitoring data of selected parameters.	Good reporting tool for surface water assessment but limited number of parameters can be incorporated.

		there. Low flexibility and average measurability.	becomes more flexible by incorporating sub-index value from pre-existing literature.		
CCME-WQI	Good reporting tool. Spatio-temporal comparison can be assessed easily. No limitation in parameter selection. High flexibility. High measurability. Non-linear data aggregation without weight calculation.	Non-linear, complex to calculate, data aggregation is done without weighting.	Recommended by many researchers for assessing overall water quality. Use is universal in context of measured limitations.	Absence of monitoring data of selected parameters	Ideal for river Churni as it allows more parameters to be incorporated. As the pollution is of diffused type evaluation of multiple parameters is essential.
OWQI	Good reporting tool.	Limitations in selecting parameters. Weighting is ambiguous. Low flexibility.	Surface and ground water for drinking purposes can be assessed.	Absence of monitoring data of selected parameters	Not ideal due to low flexibility and ambiguous weighting method.

Flexibility is identified as a weakness in SWOT analysis by Fortes et al. (2023). But they also conclude that it is desirable WQI characteristics in assessment of pollution. Thus flexibility is given importance to avoid the restrictions in selecting the parameters to prepare a well defined modelling.

Conclusion and Future approaches

The results of the study indicate that the Churni River is experiencing a huge pollution load from some point and some nonpoint sources. It is measured that the water quality is below the standard level throughout the stretch. Application of different water quality indices generates different WQI values to interpret the pollution level. All three WQIs (viz., NSF-WQI, CCME WQI, OWQI) validate the fact that sampling site 1 (S-1) is more highly affected by the pollution than the other two sampling sites (S-2 and S-3). Sampling site-3 (S-3) shows little higher value of CCME WQI than the others depicting the fact that the pollution level is slightly less in the lower stretch of the river. This may be due to the tidal effect of the river, which has no influence on the upper stretch of the river. SWOT analysis proved that CCME WQI method is the most suitable WQI assessment method in case of river Churni mostly due to its universal approach and high flexibility. In this study, all over pollution index has been studied on the basis of different sampling sites. There are more opportunities for the future researchers to study extensively considering monthly data instead of seasonal data of any river. Incorporation of more WQI analysing methods can make the study more reliable scientifically.

Conflict of Interests

Author wants to announce that there is no conflict of interest with anybody or any institution regarding this research work.

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Chapter- 21

The potential and challenges for the development of booming fertilizer trade and commerce across Iran, Afghanistan and Pakistan through the Belt and Road Initiative (BRI) from multiple perspectives

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Keywords: Afghanistan, Belt and Road Initiative, BRI, fertilizer, Iran, Pakistan, socio-economic, socio-political

Abstract:

The Belt and Road Initiative (BRI) could potentially address several challenging factors associated with fertilizer trade and food security in Iran, Afghanistan, and Pakistan through investments in infrastructure, such as transportation networks and ports, that could improve the efficiency of fertilizer trade by reducing transportation costs and enhancing connectivity between the countries. Such projects could streamline customs procedures and regulations, making importing and exporting fertilizers easier and more cost-effective, thereby improving access to agricultural inputs and enhancing food security. BRI funding could be directed towards modernizing agricultural practices, improving irrigation systems, and increasing agricultural productivity, contributing to the region's food security. The BRI partnerships could facilitate the transfer of agricultural technologies and know-how, helping farmers in these countries adopt more efficient and sustainable farming practices, leading to increased yields and improved food security. This initiative could support capacity-building programs to enhance the skills and knowledge of farmers and agricultural professionals in areas such as fertilizer use, crop management, and post-harvest handling, ultimately improving food security outcomes. Furthermore, BRI could promote regional cooperation and integration in the agricultural sector, leading to greater collaboration in research and development, sharing best practices, and coordinated responses to common challenges, which would benefit food security efforts across the region. By addressing these challenging factors through infrastructure development, trade facilitation, investment in the agricultural sector, technology transfer, capacity building, and regional cooperation, the BRI has the potential to significantly improve the ground situation related to fertilizer trade and food security in Iran, Afghanistan, and Pakistan.

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Introduction:

The Belt and Road Initiative (BRI), proposed by China in 2013, is a colossal infrastructure and economic development project aimed to connect Asia with Africa and Europe through land and maritime networks (Johnston, 2019). This ambitious venture has the potential to significantly impact global trade, economic development, and infrastructure enhancement, particularly in countries along the proposed routes. The few countries that stand to benefit from the BRI are Iran, Afghanistan, and Pakistan, and the initiative might have a profound impact on the evolution of fertilizer use and the improvement of agricultural production in this region. The geopolitical region of Iran, Afghanistan and Pakistan has a long history of agriculture and has been facing challenges in its agricultural sector, including issues related to using fertilizers. With a growing population and increasing demand for food production, there is a critical need to enhance agricultural practices and increase crop yields. Fertilizer use in this region has been influenced by factors such as technological access, government policies, and international trade barriers. Historically, these countries have depended on imports to meet their fertilizer needs, leading to vulnerabilities in their agricultural supply chain (Santra et al., 2015; Mobley, 2019).

The BRI has led to increased infrastructure development in Iran, Afghanistan, and Pakistan, including projects related to fertilizer production. This could boost agricultural productivity in the region by improving access to essential resources. However, the impact on the environment, local communities, and economic dynamics would depend on the specific details of each project and how they are implemented. Environmental concerns, such as water usage and pollution, should be carefully managed to ensure sustainable development (Shang and Shang, 2019). Additionally, the economic benefits must be distributed equitably to address potential social disparities.

Furthermore, the BRI could facilitate technology transfer and knowledge exchange in agricultural practices, including efficient fertilizer use. With increased connectivity and collaboration among BRI-participating countries, may have the opportunity to benefit from the experiences and best practices of other nations in addressing agricultural challenges (Rolland, 2017). This could lead to adopting more sustainable and effective fertilizer use practices, ultimately contributing to enhanced agricultural production and food security in this highly vulnerable geopolitical (Huang, 2016).

Points of contention between Iran, Afghanistan and Pakistan

Several socio-economic, socio-cultural, and socio-political parameters contribute to the economic growth of a country. A stable political environment reduces uncertainty for businesses and investors, and fostering economic growth together with strong legal institutions, property rights protection, and contract enforcement are essential for economic development (Huang, 2016). Adequate infrastructure, including transportation, energy, and communication networks, facilitates trade, investment, and productivity growth. Investing in education and healthcare improves the quality of the workforce, leading to higher productivity and innovation and efficient financial systems provide capital for investment, entrepreneurship, and economic expansion (Rolland, 2017). Furthermore, labour regulations that balance worker protections with flexibility for businesses can promote employment and competitiveness together with open and fair trade policies that can further encourage international investment, export growth, and access to new markets (Shang and Shang, 2019). Responsible fiscal management, including balanced budgets and sustainable debt levels, and effective monetary policies that manage inflation and promote price stability support long-term investment and economic expansion is crucial for the economic stability and growth of a country (Hughes et al., 2020)

Ensuring social equity, reducing income inequality, and addressing poverty enhance political stability and foster sustainable growth of a modern nation-state. Encouraging innovation, research and development, and technology adoption drive productivity gains and economic advancement while balancing economic growth with environmental conservation and sustainability ensures long-term prosperity for future generations. Lastly, efficient and transparent governance reduces corruption, fosters trust, and attracts investment, promoting economic growth (Mobley, 2019). These parameters interact in complex ways, and their importance may vary depending on a country's specific context and stage of development. Addressing these factors comprehensively can create an environment conducive to sustained economic growth. Sustainable economic growth typically requires a stable geopolitical environment and an active government to create and enforce policies conducive to growth (Teo et al., 2019). Geopolitical instability can deter investment, disrupt trade, and impede economic development. Additionally, an active government is often necessary to provide infrastructure, regulate markets, and invest in education and healthcare, all essential for sustained economic growth. Achieving sustainable economic growth without these factors becomes much more challenging (Dunford and Liu, 2019).

While the BRI presents significant opportunities for the agricultural sector of Iran, Afghanistan, and Pakistan, some challenges and considerations need to be addressed (Chan, 2018). The geopolitical regions of Iran, Afghanistan, and Pakistan have historically been the center of numerous flash points and geopolitical crises (Teo et al., 2019). The international boundaries of these three adjoining countries have evolved, and their complex inter-relationships have been shadowed due to a lack of trust, cooperation, investment, and successful diplomatic engagements, numerous wars and border skirmishes, insurgency, finger pointing at one another on various global, regional and local issues as well as serious ethnic tensions (Dunford and Liu, 2019). The points of contention between Iran, Afghanistan, and Pakistan have been discussed below to understand the complexity of the situation better (Cheng, 2016).

A. Between Iran and Afghanistan: The relationship between Iran and Afghanistan is complex, characterized by a mixture of cooperation and conflict, influenced by historical, cultural, religious, and geopolitical factors. Iran and Afghanistan have had several points of conflict over the years, including:

Border Disputes: The two countries share a long border, and disputes over the exact demarcation of the border have been ongoing. This has led to occasional clashes between border guards and tensions between the two governments.

Ethnic and Tribal Dynamics: Afghanistan is home to various ethnic groups, including Pashtuns, Tajiks, and Hazaras. Iran has historically supported certain ethnic and tribal factions, which has sometimes exacerbated tensions within Afghanistan.

Religious Differences: Iran is predominantly Shia Muslim, while Afghanistan is primarily Sunni Muslim. This religious divide has occasionally been a source of tension, particularly as Iran seeks to expand its influence in the region.

Political Interference: Both countries have accused each other of interfering in their internal affairs, including supporting opposition groups and insurgents. Iran has been accused of supporting certain Afghan militias, while Afghanistan has accused Iran of backing the Taliban.

Water Resources: The Helmand River originates in Afghanistan and flows into Iran and has been a source of contention. Disputes over water usage, dam construction, and irrigation rights have strained relations between the two countries.

Refugee Issues: Iran hosts a significant population of Afghan refugees, and tensions have arisen over issues such as repatriation, refugee rights, and the socioeconomic impact of hosting such a large refugee population.

B. Between Iran and Pakistan: One of the main points of contention between Pakistan and Iran is the issue of cross-border terrorism, particularly concerning militant groups operating in the region. Iran has accused Pakistan of not doing enough to prevent these groups from using Pakistani territory as a base for launching attacks on Iran. Additionally, there have been disagreements over various regional issues, including water resources and the influence of external powers in the nation (Dunford and Liu, 2019). Recently, there were unprovoked missile attacks made by both countries inside each other's border areas, claiming to decimate terrorist groups operating in the region as a counter-insurgency initiative, further deteriorating the relationships between two highly volatile neighbors in the region (Chen et al., 2019). These issues contribute to a complex and often strained relationship between the two countries.

C. Between Afghanistan and Pakistan: The main points of contention between Afghanistan and Pakistan include:

Border Disputes: Afghanistan and Pakistan have a long-standing border dispute, particularly regarding the Durand Line, drawn by the British in 1893. Afghanistan does not recognize it as an international border, leading to tensions over territorial claims.

Alleged Support for Insurgents: Afghanistan accuses Pakistan of providing safe havens and support to militant groups, including the Taliban and Haqqani Network, which operate in Afghanistan, leading to instability and violence in the region.

Refugee Crisis: Pakistan hosts millions of Afghan refugees, which strains its resources and creates social and economic challenges. Afghanistan accuses Pakistan of not doing enough to repatriate refugees and facilitating their return to Afghanistan.

Water Management: Both countries share water resources from rivers like the Kabul River, leading to disagreements over water management and usage, particularly regarding dam construction and irrigation projects.

Influence in Afghanistan: Pakistan is accused of seeking to exert influence in Afghanistan by supporting certain factions or groups, which Afghanistan perceives as interference in its internal affairs.

Are there any common grounds for developing better sociopolitical, sociocultural, and socioeconomic relationships between Iran, Afghanistan, and Pakistan?

Fostering better socio-political, socio-cultural, and socio-economic relationships between Iran, Afghanistan, and Pakistan could be achieved through various means, as discussed below. By focusing on these areas of common interest and addressing shared challenges, Iran, Afghanistan, and Pakistan can work towards building stronger socio-political, socio-cultural, and socio-economic relationships for the benefit of their populations and the region as a whole (Dunford and Liu, 2019).

Diplomatic Engagement: Regular diplomatic dialogues and initiatives to address common challenges and enhance cooperation in areas of mutual interest.

Trade and Economic Cooperation: Strengthening economic ties through trade agreements, joint ventures, and infrastructure development projects to promote prosperity and stability in the region.

Cultural Exchange Programs: Facilitating cultural exchanges, promoting tourism, and encouraging people-to-people interactions to foster understanding and appreciation of each other's cultures.

Security Collaboration: Collaborating on security issues such as counterterrorism, border security, and narcotics control to address shared threats and promote regional stability.

Educational Collaboration: Encouraging academic and educational cooperation, including student exchanges, joint research initiatives, and capacity-building programs to enhance human capital development in the region.

Infrastructure Development: Investing in regional connectivity projects like transportation networks and energy pipelines to facilitate trade and economic integration.

Environmental Cooperation: Addressing environmental challenges, such as water management and natural resource conservation, through collaborative efforts and shared solutions.

Conflict Resolution: Supporting efforts to resolve conflicts and promote reconciliation within and between the countries to create a conducive environment for cooperation and development.

How can BRI address and resolve the long-standing geopolitical instability of the Iran, Afghanistan, and Pakistan geographical regions to facilitate fertilizer trade to thrive in the region and improve the face of agriculture?

Agricultural productivity and food security in the Iran, Afghanistan, and Pakistan regions varied due to political instability, climate conditions, and economic challenges (Cheng, 2016). Afghanistan faced significant challenges due to ongoing conflict, which disrupted agricultural activities and hindered food security efforts. Pakistan has been trying to improve agricultural productivity through various initiatives and technological advancements, but disparities in access to resources and infrastructure have persisted (Dunford and Liu, 2019). Iran, while facing its own set of challenges, had relatively more stable agricultural productivity and food security compared to Afghanistan and Pakistan.

The BRI presents an opportunity for this region to improve its access to fertilizers and modern agricultural technologies. As the initiative aims to enhance infrastructure and connectivity across the region, it could facilitate the transportation of fertilizers, potentially reducing logistical barriers and costs associated with imports. Improved connectivity through the development of road and rail networks under the BRI could lead to more efficient transportation of fertilizers into the country, thereby contributing to the development of its agricultural sector (Mobley, 2019). The BRI could address the geopolitical instability in the Iran, Afghanistan, and Pakistan by fostering economic cooperation and infrastructure development. Suggested steps are as follows:

Infrastructure Investment: BRI could invest in building roads, railways, and ports in the region, facilitating smoother trade routes for fertilizer and other agricultural goods. Improved infrastructure can also enhance connectivity and promote economic integration, contributing to stability.

Economic Development: Promoting economic development and job creation through BRI projects could reduce poverty and address some of the underlying causes of instability in the region. Stable economies are less prone to conflict.

Cross-border Cooperation: BRI projects often involve cooperation between neighboring countries. Encouraging collaboration between Iran, Afghanistan, and Pakistan through joint infrastructure projects can build trust and promote stability.

Energy Cooperation: The BRI could facilitate energy cooperation between these countries, potentially easing tensions over resource access. Investing in renewable energy projects could help address energy shortages and support sustainable agricultural practices.

Diplomatic Engagement: BRI provides a platform for diplomatic engagement between countries. It could facilitate dialogue and conflict resolution efforts byBringing together stakeholders from Iran, Afghanistan, Pakistan, and other relevant nations.

Security Cooperation: BRI projects could include provisions for security cooperation to address common security challenges in the region, such as terrorism and drug trafficking, which can undermine stability and economic development.

While the BRI alone may not be a panacea for all the geopolitical challenges in the region, it can play a constructive role in addressing some of the root causes of instability and creating conditions conducive to thriving fertilizer trade and agricultural development.

Is a major global economic powerhouse like India staying away from the BRI initiative? How and where can India's absence impact the success of BRI in the region?

India's decision to stay away from the BRI largely stems from concerns about sovereignty, territorial integrity, and the China-Pakistan Economic Corridor passing through disputed territory. India views the BRI as infringing its sovereignty and undermining its strategic interests. India's decision to stay away from the BRI reflects its strategic calculations. It could have significant implications for the initiative's success in the region, particularly regarding economic integration, geopolitical dynamics, and regional stability. India's absence from the BRI could impact its success in the region in several ways:

Economic Impact: India's economy is significant, and its participation in the BRI could have added substantial economic value to the initiative. Its absence means a potential loss of investment and market opportunities for India and BRI participating countries.

Regional Connectivity: India's exclusion could hinder the BRI's goal of enhancing regional connectivity, as India plays a crucial role in South Asian and Indian Ocean trade and transportation routes. With India's involvement, the BRI may be able to achieve comprehensive connectivity in the region.

Geopolitical Dynamics: India's absence underscores the regional geopolitical tensions and rivalries, particularly between India and China. This could further complicate diplomatic relations and affect the region's stability, potentially deterring other countries from fully engaging with the BRI.

Alternative Initiatives: India's absence might prompt other regional powers or international actors to propose alternative infrastructure and connectivity initiatives, potentially diluting the BRI's influence and reach.

How can BRI help develop the fertilizer trade in Central Asia including Iran, Afghanistan, and Pakistan?

The importance and export of fertilizers for agricultural productivity have significant potential to increase under the BRI. As the BRI promotes infrastructure development and connectivity across countries, it opens up opportunities for increased fertilizer trade, enhancing agricultural productivity and food security in participating nations (Mobley, 2019). Additionally, improved transportation networks facilitated by the BRI can help streamline fertilizer distribution, benefiting producers and consumers.

BRI provides a framework for collaboration and investment that can contribute to developing the fertilizer trade in Central Asia, benefiting the agricultural sectors of Iran, Afghanistan, and Pakistan, and fostering regional economic integration. The BRI can facilitate the development of the fertilizer trade in Central Asia, including Iran, Afghanistan, and Pakistan, through various means, as discussed below.

Infrastructure Development: BRI projects often involve the construction of transportation infrastructure such as roads, railways, and ports. Improved infrastructure can enhance the movement of fertilizers within the region, reducing transportation costs and increasing accessibility.

Trade Agreements and Cooperation: BRI encourages bilateral and multilateral agreements between countries. This can lead to establishing trade agreements that facilitate the exchange of fertilizers among Central Asian countries, Iran, Afghanistan, and Pakistan, reducing trade barriers and promoting cooperation.

Investment in Production Facilities: BRI investments can support establishing fertilizer production facilities in the region, leading to increased local production and reduced reliance on imports. This can help meet the growing demand for fertilizers in agriculture-dependent economies.

Logistical Efficiency: BRI projects focus on improving logistical efficiency, which can streamline the fertilizer supply chain. This includes initiatives like customs facilitation, harmonization of regulations, and development of trade corridors, all of which can reduce delays and costs associated with transporting fertilizers.

Technology Transfer: BRI initiatives often involve technology transfer and knowledge-sharing opportunities. This can enable the adoption of advanced fertilizer production technologies, improving efficiency and sustainability in the fertilizer industry in Central Asia.

How can the vast rural underprivileged rural populations of Iran, Afghanistan, and Pakistan benefit from the fertilizer trade boosted by BRI?

Leveraging the fertilizer trade boosted by BRI can contribute to the socio-economic development of rural populations in Iran, Afghanistan, and Pakistan by enhancing agricultural productivity, creating employment opportunities, improving infrastructure, and facilitating access to markets and technology. The BRI can potentially benefit the rural populations of Iran, Afghanistan, and Pakistan in several ways through the fertilizer trade:

Increased agricultural productivity: Access to affordable fertilizers can enhance soil fertility and crop yields, thus improving food security and income for rural farmers.

Job creation: Expansion of the fertilizer trade can stimulate economic activity in rural areas, creating job opportunities in the distribution, transportation, and agricultural sectors.

Infrastructure development: BRI projects often involve infrastructure development, such as roads, railways, and ports, which can improve connectivity for rural areas, facilitating the distribution of fertilizers and agricultural products.

Technology transfer: BRI investments may facilitate the transfer of agricultural technology and best practices, improving farming techniques and efficiency in rural communities.

Market access: Improved transportation networks and trade agreements associated with BRI can provide rural farmers with better access to regional and international markets for their agricultural products.

Foreseeable challenges

Infrastructural development can significantly contribute to the economic prosperity of a region or country. Improved infrastructure such as transportation networks, communication systems, energy facilities, and water resources can enhance productivity, reduce transaction costs, attract investments, stimulate trade and commerce, and foster overall economic growth and development (Huang, 2016). However, there are limitations. Better regional connectivity through the BRI initiative can certainly help in the export-import pathways, but it is debatable whether it can facilitate trade prospects and proper use of fertilizers within the country (Johnston, 2019). The lack of formal education, awareness, and necessary training in properly using the available fertilizers, understanding the recommended dosages of applications at the right stage and correct soil types, lack of any proper storage facility for unused fertilizers, their distribution among the farmers operating in the remote, rural agronomic region with difficult terrain are some of the ground challenges (Shang and Shang, 2019).

The Iran-Afghanistan-Pakistan region is an extremely socio-politically disturbed geographical region, and it is an important point to consider in order to better understand how fertilizers could be judiciously used in the region. The operating local warlords and their belligerent militia and their constant fights with the government forces and the administration for dominating one another have long-term impacts from multiple perspectives. Hence, infrastructure development is one of many solutions to every complex issue stemming from this geopolitical region (Huang, 2016). So, BRI will transform the region without any challenge (s) is a distant dream with no real ground in it other than geopolitical propaganda. Environmental sustainability and responsible use of fertilizers are paramount concerns that must be integrated into any potential increase in fertilizer use (Shang and Shang, 2019). Additionally, Iran will need to navigate geopolitical and economic complexities associated with participating in the BRI, ensuring that its agricultural interests align with its broader strategic objectives (Johnston, 2019).

The BRI has the potential to significantly influence the evolution of fertilizer use in Iran, Afghanistan, and Pakistan which can contribute to the improvement of agricultural production. By enhancing connectivity, facilitating technology transfer, and addressing logistical barriers, the initiative could help Iran overcome challenges related to fertilizer access and the adoption of modern agricultural practices (Cheng, 2016). However, it is essential for the policymakers of these three countries to very carefully navigate the opportunities and challenges presented by the BRI to ensure that the agricultural sector reaps sustainable benefits while contributing to the country's overall development (Dunford and Liu, 2019). As this vulnerable region continues to engage with the BRI, strategic and well-informed decisions will be crucial in harnessing the potential of the initiative for the betterment of its agricultural sector and the broader economy; otherwise, it may take an unfortunate negative turn that will be beyond redemption (Mobley, 2019).

Conclusion

The BRI could significantly influence the fertilizer trade and economic development in Iran, Afghanistan, and Pakistan due to several geopolitical factors, such as monumental infrastructure development. The BRI projects could enhance transportation infrastructure, facilitating the movement of fertilizers between these countries. Improved roads, railways, and ports could reduce transportation costs and increase trade opportunities. Closer economic ties fostered by the BRI could increase fertilizer trade among these nations. Iran, Afghanistan, and Pakistan may seek to leverage their geographic proximity and BRI investments to enhance bilateral trade partnerships. BRI projects may attract foreign investment in fertilizer production and distribution infrastructure in these countries. This could lead to increased local production, job creation, and economic development. Economic development spurred by the BRI could contribute to greater regional stability, reducing political tensions and creating a conducive environment for fertilizer trade and investment.

Cooperation on energy projects under the BRI could enhance access to natural gas and other resources necessary for fertilizer production, potentially reducing production costs and increasing competitiveness in the global market. Increased fertilizer trade and production could raise environmental concerns like pollution and resource depletion. BRI initiatives may include provisions for sustainable development practices to mitigate these issues. In summary, the geopolitical impacts of the BRI have the potential to reshape the fertilizer trade and economic development landscape in Iran, Afghanistan, and Pakistan by fostering infrastructure development, enhancing trade relations, attracting investment, promoting regional stability, facilitating energy cooperation, and addressing environmental challenges.

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