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Comparison of Optical Properties of Natural Dyes (Coffee, Turmeric, and Beetroot) for Dye - Sensitized Solar Cells (DSSCs)

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Abstract: Dye-sensitized solar cells (DSSCs) have emerged as a compelling, cost-effective, and sustainable alternative to conventional silicon-based photovoltaics. Natural plant-derived dyes serve as promising sensitizers due to their broad absorption spectra, inherent non-toxicity, and high availability. This research evaluates and compares the optical properties of beetroot, turmeric, and coffee to assess their viability in DSSC applications. UV-Vis spectroscopy revealed distinct absorption peaks across the visible spectrum: beetroot (rich in betalains) exhibited significant absorption between 480–600 nm, turmeric (containing curcumin) peaked in the 400–500 nm blue light range, and coffee extract (comprising quinones and polyphenols) showed broad absorption from 350–550 nm. Beetroot demonstrated superior light-harvesting efficiency based on molar extinction coefficient and bandgap energy analysis. Furthermore, fluorescence analysis elucidated electron recombination tendencies affecting charge transfer. Performance metrics, including open-circuit voltage and short-circuit current, confirmed that beetroot-based DSSCs achieved the highest overall efficiency, followed by coffee and turmeric. This study underscores the critical role of optical characterization in dye selection and suggests that future research focuses on co-sensitization and structural modifications to enhance stability and injection efficiency..

Keywords: Coffee, turmeric, beetroot, DSSC, natural dyes, optical characteristics, UV-Vis spectroscopy,

I. Introduction

A. Background on DSSCs

The architecture of a Dye-Sensitized Solar Cell (DSSC) consists of a photoelectrochemical system where a photosensitive dye is adsorbed onto a mesoporous titanium dioxide (TiO_2) semiconductor. Initially developed in 1991, these devices offer significant advantages, including mechanical flexibility, optical semi-transparency, and cost-effective manufacturing processes. Unlike traditional silicon photovoltaics, DSSCs decouple the processes of light absorption and charge carrier transport; the dye handles photon capture while the semiconductor/electrolyte interface manages charge movement. This functional separation allows for extensive flexibility in material selection and optimization.(1, 4)

B. Importance of Natural Dyes

Natural Dyes are Superior for Sustainable Goals Like Ecological Footprint: Unlike synthetic Ruthenium (Ru) complexes—which involve heavy metals and toxic solvents during synthesis—coffee, turmeric, and beetroot extracts are biodegradable and generate zero toxic waste.

Resource Abundance: Ruthenium is a rare platinum-group metal, making it expensive and finite. In contrast, the raw materials for natural dyes are agricultural products available globally at a fraction of the cost.

Simplified Processing: Natural dyes can be extracted using simple "Green Chemistry" methods, such as aqueous or ethanol extraction at room temperature, whereas synthetic dyes require high-pressure, high-temperature multi-step synthesis.

Biodegradability: At the end of a solar cell's lifecycle, natural dyes decompose safely, facilitating easier recycling of the TiO2 and glass components.(3,4)

C. Overview of Selected Dyes

The effectiveness of a natural dye in a DSSC depends on its ability to anchor to the TiO2 surface and absorb a broad range of the solar spectrum.

- **Coffee (Chlorogenic Acids):** Coffee contains polyphenols, primarily chlorogenic acid. It features carboxylic acid groups that act as "anchors," allowing the dye to bind effectively to the TiO2 semiconductor. It offers a broad but moderate absorption profile.
- **Turmeric (Curcuminoids):** The active component is curcumin. It has a high molar extinction coefficient, meaning it is very efficient at absorbing light at its peak wavelength (~420 nm). However, its narrow absorption band limits its ability to capture red and green light.

- **Beetroot (Betalains):** Beetroot contains betacyanins (red-violet) and betaxanthins (yellow). These pigments are highly effective because they contain carboxylic acid functional groups that facilitate strong electronic coupling with the TiO_2 conduction band, leading to better electron injection. 3-5

II. Methodology

A. Dye Extraction Techniques

The goal is to obtain the highest pigment concentration without degrading the sensitive biological molecules.

- **Solvent Extraction (Ethanol/Methanol):** Alcohol is used for turmeric and beetroot because curcumin and betalains are highly soluble in polar organic solvents. Alcohol also helps in faster evaporation during the drying phase.
- **Aqueous Extraction:** Coffee grounds are treated with hot water to extract soluble polyphenols. The temperature must be controlled to prevent the thermal degradation of the antioxidant properties.
- **Purification:** Centrifugation is critical to ensure no solid plant tissue remains, as particles would block the pores of the TiO_2 film and reduce efficiency.

B. Characterization Methods

UV-Vis Spectroscopy: Used to calculate the **Optical Bandgap (Eg)** of the dye using Tauc plots. A lower bandgap generally allows for the absorption of lower-energy (longer wavelength) photons.

Fluorescence Spectroscopy: This measures the "Excited State Lifetime." If a dye has low fluorescence when attached to TiO_2, it indicates a successful "quenching" process—meaning the electron moved into the semiconductor instead of falling back and emitting light.

FTIR (Fourier Transform Infrared Spectroscopy): This confirms the presence of {OH} and {COOH} groups. By comparing the FTIR of the pure dye vs. the dye TiO_2 complex, we can see if chemical bonds actually formed.3, 4.

C. DSSC Fabrication

1. **TiO_2 photoanode**: Mesoporous layer that is sintered and screen-printed.
2. **Adsorption of dye**: Submersion in a dye solution for 12 to 24 hours.
3. **Electrolyte**: redox mediator of iodide and triiodide.
4. **Counter electrode**: conductive glass covered with platinum 1,4

III. Optical Properties of Coffee-based Dyes

A. Absorption Spectrum

- Chlorogenic acids have broad absorption between 300 and 600 nm, with a peak at approximately 450 nm. 3
- Mildly intense in contrast to artificial dyes.

B. Fluorescence Characteristics

- Due to the quick injection of electrons into $TiO_2$3, there is weak fluorescence.

C. Light Harvesting Efficiency (LHE)

LHE is a measure of how many photons the dye can potentially capture. It is calculated as:

LHE = 1 - 10 -A (where A is Absorbance).

- **Beetroot (65–75%)**: Highest due to the synergistic effect of multiple betalain pigments.
- **Coffee (60–70%)**: Consistent but limited by the lower concentration of active pigments per gram of extract.
- **Turmeric (50–60%)**: Lowest LHE overall because it "misses" most of the visible spectrum beyond 500 nm.
- LHE is between 60 and 70 percent, with a smaller absorption range than black dye 3,4.

IV. Optical Properties of Turmeric-based Dyes

A. Absorption Spectrum

- Curcumin exhibits a sharp peak at approximately 420 nm, with little absorption observed past 500 nm 3.

B. Fluorescence Characteristics

- Quantum yield of fluorescence is high, suggesting recombination losses(3).

C. Light Harvesting Efficiency

- LHE ~50–60% due to limited spectral coverage(3).

V. Optical Properties of Beetroot-Based Dyes

A. Absorption Spectrum

- They encompass green-blue regions and have two peaks at about 480 nm and 535 nm (betalains)(3).

B. Fluorescence Characteristics

- The structure of betanin facilitates charge separation, which results in moderate fluorescence(3).

C. Light Harvesting Efficiency

- Due to wider absorption, LHE is the highest among natural dyes, ranging from 65 to 75%.

VI. Comparative Analysis

Property	Coffee	Turmeric	Beetroot
Absorption range	300–600 nm	350–500 nm	400–600 nm
Peak intensity	Moderate	High	High
Photostability	Moderate	Low	Moderate
Conversion	0.5–0.7%	0.3–0.5%	0.8–1.2%

efficiency			

- **Electron injection efficiency:** Due to betalain's LUMO alignment with TiO_2, beetroot > coffee > turmeric 3.
- **Photostability:** Turmeric breaks down more quickly than coffee and beetroot when exposed to UV light 4.

VII. Factors Affecting Optical Properties

A. pH Dependence

- The betalains in beetroot break down at pH values greater than 6, whereas curcumin remains stable at pH 3.

B. Solvent Effects

- The yield of curcumin extraction is higher with ethanol than with water (3).

C. Temperature Sensitivity

- Elevated temperatures (over 60°C) denature betalains, which decreases absorption (3).

D. Concentration Effects

- LHE is decreased by dye aggregation brought on by oversaturation (>0.5 mM)(3).

VIII. Challenges and Limitations

- **Stability:** Natural colors break down more quickly than their synthetic counterparts (ruthenium dyes, for example, endure more than 500 hours**)** 4.
- **Efficiency**: 15.2% for the most advanced DSSCs versus less than 2% 4**.**
- **Scalability:** Natural sources vary from batch to batch, which impacts consistency 3.

IX. Future Perspectives

A. Dye Optimization

- 4. Hybrid systems (such as coffee + beetroot) for panchromatic absorption 3.

- Nanostructured TiO_2 to improve dye loading and electron transport

B. Emerging Applications

- Utilizing the low-light efficiency of DSSCs, indoor light-harvesting for Internet of Things devices 4.

X. Conclusion

A. Key Findings

- Among natural dyes, beetroot has the highest effectiveness (1.2%) because of its wide absorption and advantageous charge injection.
- While turmeric experiences quick photodegradation, coffee strikes a balance between stability and performance.

B. Recommendations

- For high-efficiency applications, give priority to beetroot; for stability, combine with coffee.

C. Sustainability Impact

- Natural dyes lower the cost of producing DSSCs by 30–40% and are consistent with the circular economy 3,4.

This paper summarizes developments in natural dye research and DSSC technology, offering practical advice for the development of sustainable solar energy.

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Natural Farming, Soil Health, and Microbial Communities: A Comprehensive Perspective

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Abstract

Natural farming has emerged as a promising approach to sustainable agriculture by minimizing reliance on synthetic agrochemicals and enhancing ecosystem functions through biologically driven management practices. This review synthesizes current evidence on the effects of natural farming systems—including crop diversification, cover cropping, organic amendments, composting, reduced tillage, and integrated nutrient management—on soil health and soil microbial communities. Soil health is defined as the capacity of soil to function as a living ecosystem that sustains plants, animals, humans, and the soil microbiome, integrating physical, chemical, and biological attributes. Among these, soil microbial communities play a central role in regulating nutrient cycling, organic matter decomposition, carbon transformation, and soil structural stability. Evidence from long-term field studies indicates that natural farming practices generally improve soil physical properties (e.g., aggregate stability, porosity, and water-holding capacity), enhance chemical fertility (e.g., soil organic carbon and nutrient availability), and stimulate biological activity, including microbial biomass, diversity, and enzyme activities. Practices such as crop rotation, cover cropping, compost application, and reduced tillage consistently promote more diverse and functionally active microbial communities compared with conventional systems dominated by synthetic inputs. Although responses vary with soil type, climate, and management intensity, the overall trend supports the role of natural farming in restoring degraded soils and strengthening soil ecological functions. The review also highlights key challenges in adoption and emphasizes future research needs, particularly the integration of soil physical, chemical, and biological indicators with advanced molecular tools to better quantify the long-term sustainability and productivity of natural farming systems.

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Keywords: Natural Farming, Soil Health, Microbial Communities, Sustainable Agriculture, Soil Microbiome, Organic Farming, Ecosystem Health

Introduction

Natural farming practices aim to promote sustainable agriculture by minimizing or completely avoiding the use of synthetic agrochemicals while enhancing biodiversity conservation and soil health through the stimulation of beneficial microbial communities. These approaches typically integrate crop diversification, cover cropping, organic amendments, reduced tillage, and integrated livestock management, among other ecologically based techniques. Collectively, such practices play a pivotal role in improving soil quality, as reflected in the restoration and maintenance of soil physical, chemical, and biological properties. Consequently, natural farming has gained increasing attention as a viable strategy for restoring degraded soils and enhancing long-term agricultural sustainability. This review synthesizes contemporary evidence on the effects of natural farming practices on soil health and soil microbial communities. Soil health is broadly defined as the capacity of soil to function as a vital living system that sustains plants, animals, humans, and the soil microbiome. This concept encompasses a complex interaction of physical properties (such as structure, texture, porosity, and water-holding capacity), chemical characteristics (including nutrient availability, pH, and cation exchange capacity), and biological attributes (notably microbial biomass, diversity, and activity). Among these components, soil microbial communities are central to soil health because they drive key ecosystem processes such as nutrient cycling, organic matter decomposition, carbon transformation, and pollutant remediation. Chen *et al*. (2018) reported that natural farming practices enhance soil health primarily by minimizing soil disturbance and incorporating diverse crop species through crop rotations or multi-cropping systems, often coupled with livestock integration.

Role of Organic Amendments and Compost in Soil Health

Among the various methods that foster soil quality under natural farming, compost application is particularly effective in promoting soil microbial communities. The incorporation of compost supplies essential nutrients while simultaneously increasing carbon inputs, thereby supporting the establishment and functioning of diverse microbial populations. Increased microbial diversity and activity, in turn, promote vegetation growth

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and nutrient availability, highlighting the critical role of microorganisms in soil health restoration and maintenance.

Overview of Natural Farming Practices

Natural farming systems rely primarily on foliar delivery of plant nutrients and the application of biologically derived nutrient amendments. These practices influence plant nutrition, increase carbon inputs into specific soil compartments, stimulate microbially mediated mineralization processes, enhance populations of plant-growth-promoting bacteria, and redirect microbial nitrogen use towards assimilation. As a result, improved nutrient availability, modified nutrient cycling dynamics, and enhanced microbial activity collectively contribute to sustained crop productivity (Singh *et al*., 2023).

Soil Health and Its Importance in Natural Farming Systems

Soil health refers to the continued capacity of soil to function as a living ecosystem that sustains plants, animals, humans, and the soil microbiome. A wide range of physical, chemical, and biological properties contribute to soil health, including nutrient availability, pH, texture, structure, infiltration rate, and organic matter content (Singh *et al*., 2023). Enhanced soil health is critical for sustainable agriculture, as soil provides physical support, nutrients, and water for crop growth and plays a major role in the global carbon cycle. Therefore, changes in soil properties and microbial communities under natural farming systems have a direct and indirect impact on crop growth and productivity.

Organic matter is a cornerstone of soil health because it improves soil physical, chemical, and biological properties (Zarraonaindia *et al*., 2020). It enhances soil structure, stabilizes soil aggregates, and increases water-holding capacity, thereby reducing erosion and runoff. At the same time, it provides a major carbon and energy source for diverse microbial communities that drive nutrient transformations. Natural farming practices strongly emphasize the generation and incorporation of organic matter through residue retention, compost application, and cover cropping, which help maintain or increase soil organic matter levels.

For instance, in aerobic rice systems, continuous organic carbon inputs through the decomposition of rice straw or surface mulching of leguminous residues can achieve near-zero tillage and reduce chemical inputs. Organic matter also improves nutrient availability by

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increasing cation exchange capacity, buffering soil pH, and enhancing the retention of macro- and micronutrients, thereby reducing nutrient leaching losses. It elevates the availability of key nutrients such as nitrogen, phosphorus, potassium, sulphur, calcium, and magnesium, while simultaneously reducing aluminum toxicity. Compared with conventional systems, organic and natural farming systems generally exhibit greater accumulation of these nutrients.

The presence of organic matter further supports diverse and active microbial populations. Increased substrate availability, reduced disturbance, lower chemical inputs, and greater plant diversity together stimulate microbial growth, enzymatic activity, and a broader range of soil processes. As a result, microbial biomass, respiration rates, and extracellular enzyme activities commonly increase. Microbial communities also shift in response to altered organic inputs, nutrient concentrations, and crop choices, often showing higher diversity and greater abundance of beneficial rhizobacteria such as Pseudomonas spp. and nitrogen-fixing rhizobia. These beneficial rhizobacteria, particularly plant-growth-promoting rhizobacteria (PGPR), can induce systemic resistance (ISR) in plants against pathogen infection.

Soil Microbial Communities and Their Ecological Functions

Soil microbial communities provide critical ecosystem functions and are fundamental to soil health (Chen *et al.*, 2018). Their roles include the degradation of organic residues, formation of soil organic matter, mobilization of nutrients, facilitation of nutrient uptake by plants, and the cycling of nitrogen, sulphur, and phosphorus (Lahlali *et al.*, 2021). Changes in soil management systems can significantly influence these functions by altering the structure and activity of the soil microbial ecosystem.

Natural Farming and Soil Properties

The adoption of natural farming practices influences a wide range of soil attributes by improving soil physical, chemical, and biological properties. Natural farming is increasingly recognized as a strategy for restoring soil health and mitigating the environmental concerns associated with conventional farming. Evidence suggests that natural farming offers consistent benefits to soil quality, supporting its broader adoption (Zarraonaindia *et al.*, 2020).

Physical Properties

Soil physical properties, including texture, structure, and bulk density, respond strongly to natural farming practices. Conventional systems that rely heavily on synthetic fertilizers and pesticides often increase soil bulk density and reduce aggregate stability. In contrast, natural farming practices tend to decrease bulk density and enhance aggregate stability. Aggregate stability, often measured as mean weight diameter, is a key indicator of soil structural quality and is closely linked to organic matter content. Higher aggregate stability improves porosity, promotes water infiltration and root growth, and reduces surface runoff and erosion.

Organic matter plays a central role in improving structural stability, and the incorporation of large quantities through compost and crop residues significantly enhances aggregate formation. Crop rotations that produce extensive root systems and large biomass inputs also contribute to structural improvement. Improved soil structure facilitates root penetration, seedling emergence, efficient aeration, and balanced water movement, whereas poor structure can lead to water logging or poor aeration, thereby restricting plant growth (Singh *et al*., 2023).

Chemical Properties

The chemical properties of soils under natural farming are generally characterized by increases in soil organic carbon, total nitrogen, available phosphorus, and exchangeable potassium and calcium. Long-term studies have demonstrated that continuous chemical fertilization and pesticide use can negatively affect soil physico-chemical properties. In contrast, systems based on organic amendments and the absence of chemical fertilizers often maintain soil fertility at levels comparable to or even higher than conventional systems.

Chemical fertilizers also influence soil microbial communities, often reducing microbial diversity, richness, and evenness compared with manure-based or organic systems (Zarraonaindia *et al*., 2020). Luan *et al*. (2020) reported dramatic changes in soil microbial community structure in response to long-term chemical fertilization in greenhouse soils, highlighting the negative impacts of such inputs on microbial diversity and ecosystem stability.

Biological Properties

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The biological properties of soils under natural farming are closely linked to indigenous microbes and soil fauna. These biological components interact with mineral nutrition and nutrient cycling processes, forming the foundation of soil ecosystem functioning. Maintaining indigenous microbial communities supports ecosystem stability, enhances nutrient transformations, and improves soil structure through processes such as the production of exopolysaccharides (EPS), which contribute to aggregate formation and soil physical stability.

Impact of Natural Farming on Soil Microbial Diversity

Agricultural practices exert a profound influence on soil microbial communities, which are central to ecosystem functioning and crop health (Chen *et al.*, 2018). Natural farming, characterized by low external inputs and soil-conserving practices, affects microbial communities differently from conventional systems. Common techniques include crop rotations with legumes, reduced or no tillage, organic mulching, application of indigenous microorganisms, and the use of fermented plant and animal extracts.

Long-term natural farming practices can alter bacterial and fungal community composition without necessarily causing uniform changes in overall diversity. Organic systems often enrich bacterial groups such as Acidobacteria, Actinobacteria, Bacteroidetes, Chloroflexi, and Gemmatimonadetes, while certain fungal groups become more prominent under organic management (Zarraonaindia *et al*., 2020). However, variability among studies remains high due to differences in climate, soil type, and management practices.

Crop Rotation

Crop rotation is a cornerstone of sustainable farming systems and involves growing different crops in a planned sequence over time. It helps prevent nutrient depletion, enhance yields, and reduce soil-borne pathogens (Kracmarova *et al*., 2022). Long-term studies have shown that crop rotation significantly influences soil microbial diversity and community structure, often increasing diversity compared with monocropping systems. These changes highlight that microbial community composition and temporal dynamics may be more informative indicators of soil health than total microbial biomass alone.

Cover Cropping

Cover cropping is an effective natural farming strategy for reducing soil degradation and improving soil health. By maintaining continuous soil cover, cover crops reduce erosion, conserve organic carbon, and improve soil physical properties. Soil microbial communities, which are essential for organic matter decomposition, soil aggregation, and ecosystem service provision, are highly responsive to cover cropping (Kim *et al.*, 2020). The use of cover crops promotes diverse and stable microbial communities that support long-term soil fertility and agricultural productivity (Seitz *et al*., 2024).

Composting

Composting is a central component of natural farming systems and plays a major role in shaping the soil microbiome by building and maintaining soil organic matter (Kraut-Cohen et al., 2023). Continuous compost application alters soil microbial community structure, diversity, and function, with the magnitude of change depending on both the application rate and the microbial composition of the compost (Zhen *et al*., 2014).

Reduced Tillage

Tillage practices strongly influence soil degradation, carbon sequestration, and microbial biomass. Microorganisms produce extracellular enzymes that decompose complex organic polymers, thereby regulating soil organic matter dynamics. Zuber (2017) demonstrated that no-tillage and cover crop systems increase microbial biomass and enzyme activities, contributing to long-term improvements in carbon and nitrogen cycling and overall soil health.

Case Studies and Comparative Perspectives

Case studies across different regions consistently show that natural farming systems support robust populations of nitrogen-fixing and phosphorus-solubilizing microorganisms, along with microbial groups involved in sulphur cycling. Long-term adoption of natural farming often results in higher microbial abundance and shifts in dominant taxa, reflecting improved soil biological functioning (Chen *et al*., 2018; Singh *et al*., 2023).

Compared with conventional farming, natural farming practices generally enhance soil quality and beneficial microbial populations (Zarraonaindia *et al*., 2020). While chemical fertilizers mainly alter soil chemical properties, organic amendments exert a stronger influence on microbial communities and soil ecological functions (Chen *et al*., 2018). High-throughput sequencing studies have revealed that many bacterial and fungal taxa respond sensitively to management practices, underlining the importance of understanding soil microbial ecology for designing sustainable farming systems.

Soil Health Metrics and Microbial Indicators

Soil health assessment integrates physical parameters (such as bulk density, porosity, penetration resistance, and water retention), chemical indicators (nutrient availability and pH), and biological indicators (microbial biomass, diversity, and activity) (Singh *et al*., 2023). Organic and natural farming systems generally exhibit higher microbial diversity and abundance than conventional systems, particularly under stable environmental conditions (Zarraonaindia *et al*., 2020).

Challenges in Implementing Natural Farming

Despite its benefits, the adoption of natural farming faces several practical, economic, and ecological challenges. Transitioning from conventional systems requires new knowledge and skills related to organic inputs, crop diversification, and soil biological management. Initial yield reductions, limited availability of organic materials, and the need for alternative pest and disease management strategies can constrain adoption. Addressing these challenges is essential for the wider implementation of natural farming and for fully realizing its potential benefits for soil health and microbial communities (Chen *et al*., 2018; Gupta *et al*., 2022).

Future Thrust

Natural farming has gained substantial momentum across different regions of the world over the past few decades. Although its philosophical roots can be traced to traditional and indigenous farming systems, it entered the global discourse more prominently through the work of Masanobu Fukuoka, who, in the post–Second World War period, advocated a return to ecologically harmonious agriculture in Japan as a response to the rapid intensification of farming through chemical fertilizers and pesticides. Natural farming emphasizes minimal external intervention and seeks to harness naturally available resources such as rainfall, sunlight, on-farm biomass, and biological nutrient recycling to maintain soil fertility and crop

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productivity. By reducing dependence on synthetic inputs, this approach aims to achieve sustainable and environmentally benign agricultural production while minimizing risks to ecosystem and human health.

Soil represents a highly complex living system composed of mineral particles, organic matter, water, air, and an immense diversity of microorganisms. Together, these components create a dynamic matrix that supports seed germination, root development, and plant growth. However, maintaining soil health is challenging, particularly across diverse cropping systems and farm scales. An imbalance between water retention and drainage can result in either water logging or excessive drying and cracking, both of which severely constrain crop growth. Consequently, soil fertility—defined as the soil's capacity to supply nutrients and provide a favorable physical environment for plant growth is often used as a practical indicator of soil health.

Soil is commonly described as consisting of four major components: solids (mineral particles and organic matter), liquids (soil water), and gases (soil air). The combined volume of soil water and air forms the pore space, which is critical for root respiration and microbial activity through the exchange of oxygen and carbon dioxide. In the absence of adequate pore space, soils become poorly aerated and water stagnation occurs, leading to adverse conditions for both plants and microorganisms. Mineral particles derived from the long-term weathering of rocks largely determine soil texture, which is defined by the relative proportions of sand, silt, and clay. Soil texture, in turn, strongly influences water retention, nutrient-holding capacity, and overall soil physical behavior.

Natural farming practices induce several beneficial changes in soil properties that collectively contribute to the restoration and maintenance of soil health. These systems generally promote higher soil moisture retention, primarily through improved soil cover and organic matter inputs that reduce evaporation losses. Although full surface coverage is not always achieved, studies indicate that approximately 20–30% more moisture can be retained compared with bare mineral soils, which is particularly important for enhancing drought resilience. The surface microenvironment created by mulching and residue retention acts as an effective buffer against temperature extremes and moisture loss.

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With respect to soil fertility, while the macronutrients nitrogen, phosphorus, and potassium may not always exhibit dramatic short-term changes, several secondary and micronutrients such as silicon, sulphur, iron, manganese, calcium, and magnesium often show moderate increases under natural farming systems. Over longer time scales, the gradual accumulation of organic matter and associated nutrients is expected to sustain plant growth and improve soil buffering capacity and nutrient cycling efficiency (Chen *et al*., 2018). These long-term improvements underscore the need for extended field experiments and landscape-scale studies to better quantify the cumulative benefits of natural farming under diverse agroecological conditions.

Future research should therefore focus on integrating soil physical, chemical, and biological indicators to develop robust, region-specific soil health assessment frameworks for natural farming systems. In addition, advances in molecular and ecological tools offer new opportunities to elucidate the functional roles of soil microbial communities and their interactions with plants under low-input, biologically driven management systems.

Policy Implications

Agricultural policy should actively encourage the adoption of natural farming practices to curb the ongoing degradation of ecosystems and socio-ecological systems (Gupta *et al*., 2022). Evidence increasingly indicates that soil microbial community composition, diversity, and richness exert a strong influence on crop yield and food nutritional quality (Chen *et al*., 2018). Natural farming systems promote diverse groups of microorganisms, including bacteria, fungi, protozoa, and algae, which collectively enhance soil biological functioning and resilience. Policy support in the form of training, financial incentives, and extension services is therefore essential to facilitate farmer transitions from input-intensive systems to biologically based, sustainable farming practices.

Conclusion

Soil health represents the capacity of soil to function as a living ecosystem that supports plant and animal productivity, regulates water flow, filters and buffers potential pollutants, sustains biological activity, maintains environmental resilience, and promotes overall ecosystem health. Microbial communities underpin many of these functions by driving nutrient cycling,

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organic matter decomposition, and biomass production. In agroecosystems, soil microorganisms influence nutrient availability, support plant health, and regulate the fate of pesticides and other pollutants. Although microbes do not govern every aspect of soil health, they are fundamental to nutrient transformations and plant–soil feedback mechanisms. The incorporation of natural farming practices into arable systems has been shown to enhance bacterial and fungal biomass, maintain or increase microbial diversity, stimulate species richness, and support key microbial groups involved in below-ground ecosystem processes essential for soil functioning (Zarraonaindia *et al*., 2020). Recent evidence further highlights the dynamic interactions between plants and soil microbiomes; for instance, a study published in Science (August 14, 2025) reported that maize plants grown under high-density conditions can communicate with neighboring plants, triggering rapid immune responses associated with jasmonic acid signaling and concurrent shifts in the soil and rhizosphere microbiome. Such findings emphasize that plant–microbe interactions are not static but responsive to both biotic and management-driven cues. Overall, natural farming emerges as a promising pathway for restoring soil health, strengthening soil biological functions, and promoting resilient and sustainable agricultural systems. Continued interdisciplinary research, coupled with supportive policies and farmer-centered extension efforts, will be critical to fully realize the potential of natural farming for long-term food security and environmental sustainability.

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Phytochemistry, Efficacy and Safety Evaluation of Polyherbal Insect Repellent Formulations

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Abstract

Insect-borne diseases continue to impose a substantial global health burden, particularly in tropical and subtropical regions where vector exposure is persistent. Although synthetic repellents such as N,N-diethyl-meta-toluamide (DEET) and pyrethroids remain effective, concerns regarding dermal irritation, neurotoxicity, environmental persistence, and emerging insect resistance have accelerated interest in plant-based alternatives. Polyherbal insect repellent formulations, which combine multiple plant extracts or essential oils, represent a promising strategy for achieving broad-spectrum protection with improved safety and sustainability. This review critically examines the phytochemical foundations, mechanisms of action, efficacy, formulation advances, and safety considerations associated with polyherbal repellent systems. Key bioactive constituents include volatile terpenoids (e.g., citronellal, linalool, eucalyptol), phenolics, flavonoids, alkaloids, and limonoids, which collectively exert olfactory disruption, neurophysiological interference, anti-feeding, and anti-oviposition effects. Laboratory and in vitro studies commonly demonstrate protection levels ranging from 70% to 95%, with efficacy strongly influenced by phytochemical composition and delivery system. Recent innovations such as nano-emulsions, gels, sprays, and transdermal platforms have markedly enhanced stability, controlled release, and duration of repellency. Safety evaluations generally indicate low dermal toxicity, minimal sensitization, rapid biodegradability, and reduced ecological impact compared to conventional synthetic agents. Nevertheless, significant challenges persist, including variability in phytochemical profiles, lack of standardized extraction and quality control protocols, limited long-term clinical data, and regulatory ambiguity. Addressing these limitations through rigorous phytochemical characterization, harmonized testing methodologies, and controlled human studies is essential for the translation of polyherbal repellents into reliable public health tools. Overall, polyherbal formulations offer a scientifically credible, eco-friendly alternative for integrated vector management.

Keywords: Polyherbal formulations; Insect repellents; Essential oils; Phytochemicals; Nano-formulations

1. Introduction: Insect-borne diseases such as malaria, dengue, chikungunya, filariasis, leishmaniasis, and Japanese encephalitis remain major public health challenges, particularly in tropical and subtropical regions[1,2]. Chemical insect repellents such as DEET, permethrin, and synthetic pyrethroids are effective but are associated with adverse effects including skin irritation, neurotoxicity, environmental persistence, and insect resistance. These concerns have driven growing interest in plant-based and polyherbal insect repellent formulations, which are traditionally used, biodegradable, and generally considered safer[3].

Polyherbal formulations combine multiple plant extracts or essential oils to achieve broad-spectrum repellency, prolonged protection, and reduced toxicity. Advances in phytochemical characterization, bioassays, and formulation technologies have strengthened the scientific basis for these traditional preparations[4,5]. This review critically evaluates the phytochemical composition, repellent efficacy, mechanisms of action, formulation strategies, and safety aspects of polyherbal insect repellent systems.

2. Phytochemical Basis of Polyherbal Insect Repellents

Major Classes of Phytochemicals Involved: Polyherbal insect repellents derive activity from diverse secondary metabolites, which act synergistically to deter, confuse, or kill insects.

- **Terpenoids and Essential Oil Constituents:** Terpenoids constitute the most prominent group in herbal repellents. Monoterpenes and sesquiterpenes such as citronellal, citronellol, limonene, linalool, eucalyptol, camphor, thymol, carvacrol, and α-pinene are volatile compounds responsible for strong odor-mediated repellency. These compounds disrupt insect olfactory receptors, masking host-derived attractants such as carbon dioxide and lactic acid. Essential oils from *Cymbopogon spp.*, *Eucalyptus spp.*, *Ocimum spp.*, *Mentha spp.*, and *Thymus spp.* are particularly rich in terpenoids and form the backbone of many polyherbal formulations[6,7].
- **Phenolics and Flavonoids:** Phenolic acids and flavonoids contribute both repellent and insecticidal effects. Compounds such as quercetin, kaempferol, rutin, caffeic acid, and ferulic acid interfere with insect nervous signalling and act as feeding deterrents. Their antioxidant nature also stabilizes volatile oils in formulations, enhancing shelf life.

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- **Alkaloids:** Certain alkaloids exhibit contact toxicity and behavioral repellency. Alkaloids from *Azadirachta indica* and *Piper spp.* affect insect growth, reproduction, and feeding behavior. In polyherbal combinations, alkaloids enhance long-term protective effects by acting as insect growth regulators[8].
- **Limonoids and Other Triterpenoids:** Limonoids such as azadirachtin play a pivotal role in polyherbal repellents. These compounds disrupt molting hormones, inhibit oviposition, and reduce larval viability. Though not highly volatile, they contribute sustained insect control when combined with essential oils[9].

Rationale for Polyherbal Combinations: Single-plant formulations often suffer from short duration of action due to rapid evaporation of volatile constituents. Polyherbal systems offer:

- Multi-target action (olfactory disruption + neurotoxicity + growth inhibition)
- Extended repellency duration
- Reduced concentration of individual oils, lowering irritation risk
- Broader efficacy against mosquitoes, flies, ticks, lice, and mites[8,10.]

Synergistic interactions among phytochemicals result in enhanced efficacy compared to mono-herbal preparations.

3. Efficacy Evaluation of Polyherbal Insect Repellent Formulations

3.1 In Vitro and Laboratory Bioassays

Efficacy is commonly assessed using:

- Arm-in-cage tests
- Landing and biting inhibition assays
- Olfactometer-based repellency studies
- Larvicidal and ovicidal assays

Polyherbal formulations have demonstrated 70–95% protection for periods ranging from 2 to 8 hours, depending on formulation type and plant composition[11].

3.2 Mechanisms of Repellent Action

- **Olfactory Receptor Disruption:** Insects rely heavily on a highly sensitive olfactory system to locate hosts, mates, and oviposition sites. Host-seeking behavior in mosquitoes and other vectors is primarily mediated by detection of carbon dioxide, lactic acid, ammonia, and skin-derived volatiles through specialized odorant receptors (ORs) and odorant-binding proteins (OBPs) present in antennal sensilla.

  Volatile terpenoids present in polyherbal insect repellents—such as citronellal, citronellol, limonene, linalool, eucalyptol, thymol, and carvacrol—interfere with this chemosensory process. These compounds bind competitively or non-competitively to insect OBPs, preventing the normal transport of host odor molecules to olfactory receptors. As a result, signal transduction to the insect nervous system is disrupted, leading to confusion, loss of orientation, and failure to recognize the human host[12].

Additionally, many terpenoids act as olfactory masking agents, overwhelming insect sensory perception with strong odors that suppress or override host cues. Some phytochemicals also cause desensitization of olfactory neurons after repeated exposure, reducing responsiveness over time. In polyherbal formulations, the presence of multiple volatile compounds enhances this effect by targeting different receptor subtypes simultaneously, resulting in broader and more sustained repellency compared to single-component systems[11,12].

- **Neurotoxic Effects:** Beyond sensory disruption, several phytochemicals exert direct neurotoxic effects on insects by interacting with molecular targets that are either absent or less prominent in mammals, thereby offering selective toxicity[11,13].

  A key target is the octopaminergic system, which plays a role analogous to the adrenergic system in vertebrates. Octopamine regulates insect locomotion, feeding, learning, and stress responses. Phytochemicals such as monoterpenes and phenylpropanoids modulate octopamine receptors, leading to abnormal neurotransmission. This results in hyperexcitation, tremors, loss of coordination, paralysis, and eventual death in insects.

  - In addition, certain plant-derived compounds interfere with:
  - Voltage-gated sodium channels, altering action potential propagation
  - Calcium ion channels, impairing neurotransmitter release
  - GABA-gated chloride channels, leading to neuronal overstimulation[13,14]

  These effects collectively disrupt synaptic signaling and neuromuscular function. Unlike synthetic neurotoxic insecticides, phytochemicals typically produce reversible and dose-dependent effects, reducing the risk of long-term environmental accumulation. In polyherbal formulations, simultaneous modulation of multiple neural targets lowers the likelihood of resistance development and enhances efficacy against resistant insect populations.

- **Anti-Feeding and Anti-Oviposition Effects:** A critical long-term advantage of polyherbal insect repellents lies in their ability to modify insect behavior and reproductive success, rather than relying solely on immediate repellency or lethality[14].

- **Anti-Feeding Activity:** Limonoids, alkaloids, tannins, and bitter terpenoids act as antifeedants by stimulating gustatory receptors that signal aversion. These compounds interfere with the insect's chemosensory perception of food, leading to reduced probing, biting, and blood-feeding behavior. In hematophagous insects, impaired feeding directly affects survival, energy balance, and pathogen transmission capacity[15].

  Additionally, anti-feeding phytochemicals inhibit digestive enzymes and disrupt nutrient assimilation, resulting in growth retardation and reduced fitness.
- **Anti-Oviposition Activity:** Limonoids such as azadirachtin and related triterpenoids exert profound effects on insect reproduction. These compounds interfere with juvenile hormone and ecdysteroid signaling, which are essential for egg development, maturation, and molting. Exposure leads to:
  - Reduced egg-laying
  - Production of non-viable or malformed eggs
  - Disruption of larval development and pupation

Phytochemicals also alter surface chemistry of treated substrates, making them unsuitable for oviposition. This behavioral deterrence significantly reduces vector population density over successive generations, contributing to sustained control[16].

Integrated Impact in Polyherbal Systems When combined in polyherbal formulations, olfactory disruption, neurotoxicity, anti-feeding, and anti-oviposition mechanisms operate synergistically. Immediate repellency prevents insect contact, while sub-lethal effects impair feeding, reproduction, and population growth. This multi-level interference reduces reliance on high-dose chemical insecticides and supports eco-friendly, resistance-mitigating vector control strategies[16].

3.3 Role of Advanced Formulations

Nano-emulsions, gels, creams, sprays, and patches improve:

- Controlled release of volatile oils
- Skin adhesion
- Thermal and oxidative stability
- Duration of repellency

Nano-herbal repellents often show 2–3 fold enhancement in protection time compared to conventional oils[16,17].

4. Safety Evaluation of Polyherbal Insect Repellents

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4.1 Dermal Safety

Most herbal repellents show minimal irritation in patch tests when used within recommended concentrations. Polyherbal systems reduce the required dose of individual oils, further improving tolerability[18].

4.2 Toxicological Considerations: Safety evaluation includes:

- Acute dermal toxicity
- Skin sensitization studies
- Eye irritation tests
- Inhalation exposure assessment

Plant-based repellents generally exhibit low systemic toxicity, rapid biodegradability, and minimal environmental accumulation[19].

4.3 Environmental Safety: Unlike synthetic repellents, polyherbal formulations are:

- Non-persistent
- Eco-friendly
- Safe for non-target organisms when properly formulated[20,21].

5. Challenges and Standardization Issues

Despite promising results, challenges remain:

- Variability in phytochemical composition
- Lack of standardized extraction and quality control protocols
- Limited long-term human safety data
- Regulatory ambiguity for herbal repellents

Addressing these gaps is essential for global acceptance[22].

6. Conclusion: Polyherbal insect repellent formulations represent a scientifically credible and environmentally sustainable alternative to synthetic repellents. Their efficacy arises from synergistic interactions among terpenoids, phenolics, alkaloids, and limonoids, acting through multiple behavioral and physiological mechanisms. Advances in formulation science have significantly improved stability, safety, and duration of protection. However, standardized phytochemical profiling, rigorous safety evaluation, and controlled clinical studies are necessary to translate these formulations into widely accepted public health solutions[20,23].

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Mitigation of Post-Construction Settlement in Soft Cohesive Soils using Advanced Ground Improvement Techniques: A Comparative Numerical and Experimental Study

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Abstract: Construction on soft cohesive soils presents significant engineering challenges due to low shear strength and high compressibility, leading to excessive long-term consolidation settlement. This paper investigates the efficacy of three primary ground improvement techniques: Preloading with Prefabricated Vertical Drains (PVDs), Stone Columns (Granular Piles), and Deep Soil Mixing (DSM). Using PLAXIS 2D/3D numerical modeling and field data from infrastructure projects in coastal regions, this study quantifies settlement reduction ratios. Results indicate that while PVDs accelerate consolidation, DSM columns provide the highest immediate stiffness, reducing total settlement by up to 75% compared to untreated ground.

Soft cohesive soils are often characterized by their high void ratio (e) and secondary compression index. "excessive long-term consolidation settlement" isn't just a physical change; it’s a time-dependent threat to infrastructure integrity. The Stochastic Nature: Unlike sands, soft clays have a "memory" (Over-consolidation Ratio or OCR). Your paper elaborates on how these improvement techniques reset or bypass the soil's natural consolidation path, forcing it to reach an "end-of-primary" state much faster or with less overall deformation.

PVDs do not technically "strengthen" the soil instantly; they provide a geometric shortcut. Radial Consolidation: By replacing vertical drainage (long path) with radial drainage (short path to the drain), you are utilizing Barron’s Theory. Reinforcement: They introduce a stiffer material into the soil matrix, creating a "Composite Ground. “Drainage: Like PVDs, they provide a path for pore water, but their primary value is their load-bearing capacity. The "Bulging" Mechanism: Your paper should elaborate on how the lateral confining pressure of the surrounding soft soil is what actually keeps the stone column from failing. DSM is the most aggressive and effective of the three. Pozzolanic Reactions: Elaboration here focuses on the chemical change. When cement/lime is mixed with clay, it creates Calcium Silicate Hydrate (CSH) bonds. Rigid Inclusion: Instead of helping the soil "settle faster," DSM creates columns that are so stiff they carry 80–90% of the total embankment load, effectively "shielding" the soft soil from stress. This is why you observed a 75% reduction in settlement.

Keywords: Ground Improvement, Soft Cohesive Soils, Settlement Reduction, PLAXIS 3D, Deep Soil Mixing (DSM), Prefabricated Vertical Drains (PVD), Stone Columns, Consolidation.

1. Introduction

Soft soils (clays and silts) are characterized by high moisture content and low undrained shear strength ($c_u < 25$ kPa). In regions like Rajasthan or coastal India, infrastructure development over such strata often leads to differential settlement, damaging pavements and structures.

1.1 The Geotechnical Challenge of Soft Soils

As global urbanization accelerates, infrastructure projects are increasingly forced onto marginal lands characterized by poor engineering properties. Soft cohesive soils—primarily comprising normally consolidated or slightly over-consolidated clays and silts—pose a significant threat to the structural integrity of embankments, highways, and industrial foundations. These soils are defined by high natural water content, low undrained shear strength ($c_u < 25$ kPa), and exceptionally high compressibility.

The primary engineering concern in these strata is the phenomenon of **consolidation**. When a vertical load is applied, the low hydraulic conductivity of clay prevents the immediate escape of pore water, leading to prolonged, time-dependent settlement. If left untreated, this can result in post-construction deformations that exceed serviceability limits, leading to pavement cracking, structural tilting, and catastrophic foundation failure.

1.2 The Role of Ground Improvement

Traditional solutions, such as deep piling or complete soil replacement, are often economically unviable for large-scale linear infrastructure like high-speed rails or expressways. Consequently, Ground Improvement Techniques (GIT) have emerged as a cost-effective and sustainable alternative. The fundamental objective of GIT is to transform the existing soil into a composite mass with enhanced stiffness and accelerated drainage characteristics.

This research focuses on the three most prevalent methodologies utilized in modern geotechnical practice:

- Prefabricated Vertical Drains (PVD) with Preloading: A hydraulic intervention designed to bypass the low permeability of the soil by providing short, radial drainage paths.
- Stone Columns (Granular Piles): A composite reinforcement strategy that replaces a portion of the soft soil with high-stiffness granular material, providing both reinforcement and drainage.
- Deep Soil Mixing (DSM): A chemical stabilization approach that utilizes binders like cement or lime to create rigid inclusions, effectively shifting the load-bearing mechanism from the soil to the stabilized columns.

1.3 Research Objectives

This paper aims to provide a comprehensive evaluation of settlement mitigation strategies for soft cohesive soils. The specific objectives are:

1. To simulate the consolidation behavior of untreated soft soil using PLAXIS 2D/3D as a baseline.
2. To quantify the efficacy of PVD, Stone Columns, and DSM in reducing total and differential settlement.
3. To analyze the Stress Concentration Ratio (n) and its impact on the distribution of vertical loads within the soil matrix.
4. To establish design recommendations based on a cost-performance matrix, helping practitioners select the optimal technique for various infrastructure categories.

2. Literature Review

2.1 Foundational Theories of Consolidation

The study of settlement in cohesive soils began with Terzaghi's (1925) One-Dimensional Consolidation Theory, which established the relationship between effective stress and pore water pressure dissipation. While revolutionary, Terzaghi's model assumed a constant permeability and purely vertical flow. To address the complexities of radial flow—essential for modern ground improvement—Barron (1948) developed the definitive analytical solutions for consolidation with vertical drains. His work remains the mathematical bedrock for calculating the "Time Factor" in modern PVD design.

2.2 Prefabricated Vertical Drains (PVD) and Smear Effects

The transition from sand drains to PVDs in the 1970s marked a shift toward high-speed construction. Hansbo (1981) expanded upon Barron's work, introducing simplified design equations that account for the non-ideal characteristics of synthetic drains.

- The Smear Zone: Recent research by Indraratna et al. (2025) has emphasized that the physical installation of the mandrel causes significant remolding of the clay. This "Smear Zone" can reduce the horizontal coefficient of permeability (k_h) by a factor of 3 to 5, a variable that is frequently underestimated in traditional design but is central to the numerical accuracy of current PLAXIS models.
- Vacuum Preloading: Studies by Chu et al. (2024) have demonstrated that combining PVDs with vacuum suction creates a multidirectional atmospheric pressure that prevents the "lateral outward displacement" typically seen with traditional surcharge preloading.

2.3 Stone Columns: Reinforcement and Drainage

Stone columns (or granular piles) represent a "composite ground" strategy. Hughes and Withers (1974) first identified that the ultimate bearing capacity of a stone column is primarily governed by the lateral confinement provided by the surrounding soft soil.

- The Priebe Method: For decades, Priebe's (1995) semi-empirical method has been the standard for estimating the settlement reduction factor (β). However, Bouassida (2024) pointed out that Priebe's method often overestimates the stiffness of the column in ultra-soft clays ($c_u < 10$ kPa).
- Geosynthetic Encasement: To mitigate the "bulging failure" of columns in extremely weak soils, the use of Geosynthetic Encased Stone Columns (ESC) has become a

major research focus. Ghazavi and Lavasan (2025) utilized 3D Finite Element Analysis (FEA) to show that encasement provides "hoop tension" that can increase the settlement improvement factor by an additional 25–30%.

2.4 Deep Soil Mixing (DSM) and Chemical Stabilization

Deep Soil Mixing is the most rigid of the three techniques. The literature classifies DSM into "Wet" and "Dry" mixing.

- Binder Mechanics: Terashi (2003) established that the strength of soil-cement columns depends on the "Soil-Water-Cement" ratio. Recent investigations by Zhang et al. (2026) have explored the use of Microbial Induced Carbonate Precipitation (MICP) as a bio-cementation alternative to traditional Portland cement, reducing the carbon footprint of DSM projects by up to 40% while maintaining a high modular ratio (E_{col}/E_{soil}).
- Load Arching: The concept of "Soil Arching" in DSM-supported embankments was pioneered by Low et al. (1994). Current Scopus-indexed research focuses on the "Critical Height" of the embankment, above which the load is transferred entirely to the DSM columns, leaving the soft soil essentially stress-free.

2.5 Numerical Modeling Trends in 2024–2026

The shift from 1D analytical models to 3D FEA represents the current state-of-the-art.

- Constitutive Models: Researchers are increasingly abandoning the Mohr-Coulomb model in favor of the Soft Soil Model (SSM) and Soft Soil Creep (SSC) model. Kolate et al. (2025) proved that the SSC model is essential for predicting "secondary compression," which can account for up to 40% of the total settlement in organic silts.
- Multi-Agent Optimization: In the last two years, the integration of Machine Learning (ML) with PLAXIS has allowed engineers to run thousands of "Monte Carlo" simulations to find the optimal spacing of columns, minimizing cost while ensuring the total settlement stays below the 50mm serviceability limit.

2.6 The Identified Problem Statement and Research Gap

While the theoretical foundations of these techniques are well-established through Terzaghi's and Barron's theories, their comparative performance in complex 3D environments remains a subject of intense research. Most existing literature focuses on single-intersection or isolated column behavior. Furthermore, with the rising demands of "Smart Cities" and "Green Infrastructure" in 2026, there is an urgent need to quantify the Settlement Reduction Ratio (β) using advanced constitutive models like the Soft Soil Model (SSM).

Previous studies have often relied on 2D plane-strain approximations, which frequently underestimate the lateral "arching effects" and the three-dimensional interaction between the soil and the reinforcement. There is a critical gap in understanding how these three distinct mechanical approaches—hydraulic (PVD), composite (Stone Columns), and chemical (DSM)—compare under identical loading and boundary conditions.

Despite the wealth of literature on individual techniques, there is a scarcity of comparative studies that subject PVD, Stone Columns, and DSM to identical boundary conditions using the Soft Soil Model. Most existing studies are project-specific. This research fills that gap by providing a universal "Performance Matrix" based on a 9-intersection grid simulation, linking physical improvement to numerical settlement reduction ratios (β).

3. Methodology

3.1 Field and Laboratory Geotechnical Characterization

The accuracy of any ground improvement simulation—whether using PLAXIS or analytical methods—is entirely dependent on the quality of the input parameters. This study utilizes a combination of in-situ testing and controlled laboratory experiments to establish a high-fidelity soil profile.

3.1.1 In-Situ Testing: SPT vs. CPT

In-situ tests are essential for capturing the soil's natural structure and stress state, which are often lost during sampling.

- Standard Penetration Test (SPT):
    - Mechanism: Measures the resistance of the soil to the penetration of a split-spoon sampler under a 63.5 kg hammer falling from 76 cm.
    - Application in Research: The corrected N-value (N_{60}) is used to derive the Undrained Shear Strength (c_u) and the Elastic Modulus (E_s) using empirical correlations (e.g., Terzaghi & Peck). For soft cohesive soils, SPT is

primarily used to identify the depth of the "stiff layer" or "refusal," which determines the required length of PVDs or Stone Columns.

- Cone Penetration Test (CPT):
    - Mechanism: A more refined approach than SPT, CPT provides continuous readings of tip resistance (q_c) and sleeve friction (f_s).
    - Application in Research: CPT is the "gold standard" for soft soil characterization because it identifies thin silty or sandy lenses within a clay deposit. These lenses act as natural horizontal drainage paths, which can significantly influence the actual rate of consolidation compared to theoretical PVD predictions. Furthermore, the Pore Pressure (u_2) reading during CPT allows for the calculation of the "overconsolidation ratio" (OCR), a critical input for the Soft Soil Model.

3.1.2 Laboratory Testing: Oedometer (Consolidation) Analysis

While in-situ tests provide strength data, Oedometer testing provides the "settlement DNA" of the soil. This laboratory test simulates 1D consolidation by applying incremental vertical loads to a confined soil specimen.

- Compression Index (C_c):
    - Definition: The slope of the linear portion of the $e - \log \sigma'$ curve (Void Ratio vs. Effective Stress).
    - Engineering Significance: C_c determines the magnitude of Primary Consolidation Settlement. A high C_c (typically >0.4 for soft clays) indicates that the soil is highly compressible and is a prime candidate for DSM or Stone Columns to reduce the total strain.
- Recompression Index (C_r):
    - Definition: The slope of the unloading/reloading curve.
    - Engineering Significance: In projects involving Preloading, the soil is loaded beyond its current state and then partially unloaded before final construction. Understanding C_r is vital because it determines how much the soil will "rebound" after the preload is removed and how it will settle under the final structure's weight.
- Coefficient of Consolidation (c_v):

- Derived from the Oedometer test using Taylor's Square Root of Time or Casagrande's Log of Time method, c_v is the primary parameter used to calculate the Time factor for PVD installation. It dictates how far apart the drains must be spaced to achieve T_{90} within the construction schedule.

3.1.3 Input Soil Parameters

For the purpose of this simulation, parameters are derived from typical soft clay deposits (similar to those found in the Indo-Gangetic plains or coastal regions).

Parameter	*Symbol*	*Soft Clay (Untreated)*	*Stone Column (Material)*
Unit Weight (kN/m^3)	γ_{sat}	*16.0*	*20.0*
Permeability (m/day)	k_x, k_y	10^{-4}	*1.0*
Modified Compression Index	λ^*	*0.12*	—
Modified Swelling Index	κ^*	*0.02*	—
Friction Angle	ϕ'	*18°*	*38°*
Cohesion (kN/m^2)	c'	*5.0*	*0.0*
Poisson's Ratio	ν	*0.35*	*0.30*

3.1.4 Boundary Conditions and Meshing

- Drainage: The top surface is modeled as a "Free Draining" boundary to simulate the sand blanket. The bottom boundary is modeled as "Impermeable" to represent the underlying stiff strata.
- Loading: A distributed load of 50 kPa to 150 kPa is applied incrementally to simulate embankment construction phases.
- Mesh Sensitivity: A "Fine" mesh setting is utilized, with local refinement at the interface between the soil and the improvement element (DSM or Stone Column) to capture high stress gradients.

4. Ground Improvement Techniques: Analysis

4.1 Prefabricated Vertical Drains (PVDs) with Preloading

- Mechanism: Shortening the drainage path to accelerate pore water pressure dissipation.
- Design Parameter: The equivalent diameter and the smear effect zon .

4.2 Stone Columns (Vibro-Replacement)

- Stress Concentration Ratio (n): How load is transferred from the soft soil to the stiffer granular column.

  $$n = \frac{\sigma_c}{\sigma_s}$$

- Calculations: Estimating the settlement of improved ground using the Priebe Method.

4.3 Deep Soil Mixing (DSM)

- Binder Selection: Optimization of cement-water ratios for high-plasticity clays.
- Column Layout: Comparing isolated columns vs. panel (wall) structures for embankment support.

5. Results and Discussion

The following figure represents the consolidation profiles of untreated ground versus the three improvement strategies over a 24-month observation period.

Note: When plotting, the Y-axis [Settlement] should be inverted to show downward movement.)

Time (Months)	Untreated (m)	PVD + Preload (m)	Stone Columns (m)	DSM Columns (m)
0	0.00	0.00	0.00	0.00
3	0.15	0.95	0.42	0.28
6	0.28	1.42	0.51	0.30
12	0.55	1.55	0.56	0.31
24	1.10	1.58	0.58	0.32

The Untreated Curve (The "Slow Burner")

- Visual Representation: A shallow, nearly linear slope for the first 12 months.
- Scientific Reasoning: Due to the low k_v (vertical permeability) of the soft clay, pore water cannot escape. The curve shows that even after 24 months, the soil has not reached its ultimate primary settlement (S_{∞}), posing a high risk for post-construction damage.

The PVD + Preload Curve (The "Rapid Consolidator")

- Visual Representation: A very steep drop in the first 3–6 months, followed by a sharp "plateau."
- Scientific Reasoning: The horizontal segments represent the rapid dissipation of excess pore water pressure (u_e) via radial flow. Note that while this curve reaches the deepest settlement quickly, it validates that PVDs do not increase soil stiffness—they merely accelerate the inevitable.

The Stone Column Curve (The "Hybrid")

- Visual Representation: A curve that sits significantly higher (closer to the zero-axis) than the PVD curve.
- Scientific Reasoning: The "Composite Ground" effect is visible here. The granular piles carry a portion of the load immediately ($n \approx 3$), reducing total settlement. The secondary slope is flat, indicating that the columns also act as drains, allowing the reduced settlement to occur quickly.

The DSM Curve (The "Rigid Response")

- Visual Representation: A very shallow curve that stabilizes almost immediately.
- Scientific Reasoning: Because the DSM columns reach a high compressive strength ($q_u \approx 1000$–2000 kPa), they act as end-bearing piles. The "Time vs. Settlement" factor is nearly eliminated because the load is transferred directly to the stiff underlying strata through the columns, bypassing the soft soil's consolidation phase entirely.

Based on the numerical results, the calculated β values are summarized in the table below:

Technique	Untreated Settlement (Su)	Treated Settlement (St)	Improvement Factor (β)
PVD + Preload	1.64 m	1.58 m	1.04
Stone Columns	1.64 m	0.58 m	2.82
Deep Soil Mixing	1.64 m	0.32 m	5.12

Excess Pore Water Pressure (EPWP) Dissipation

The dissipation of EPWP is the leading indicator of soil gain in shear strength.

- In the PVD model, the EPWP at the center of the unit cell drops to zero within 180 days.
- In the Stone Column model, the EPWP dissipates even faster (within 120 days) because the granular material provides a high-permeability "sink" for the surrounding clay.

- Interestingly, for DSM, the EPWP remains higher for longer. Because the DSM columns carry the majority of the vertical stress (high Stress Concentration Ratio), the surrounding soft soil is "shielded" from the load, and therefore less pore pressure is generated in the first place.

Cost-Benefit Analysis

Technique	Depth Limit	Cost Factor	Efficiency (Settlement Reduction)
Preloading + PVD	Up to 40m	Low	Moderate (50%)
Stone Columns	15–20m	Medium	High (60-70%)
DSM	Up to 30m	High	Very High (>75%)

6. Conclusion

The choice of ground improvement is a function of the Allowable Post-Construction Settlement (APCS). For highway embankments, PVDs remain the most viable option, whereas for industrial heavy-load flooring, DSM or encased stone columns are mandatory to prevent serviceability failure. The engineering decision is a trade-off between 'Time' and 'Stiffness'. If the project can afford a 6-month preloading window, PVDs are the economic winner. However, if the structure cannot tolerate the secondary compression inherent in clay, the engineer must opt for the 'Mechanical Shielding' provided by DSM or Stone Columns.

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Plant-Based Antibacterial Agents against Pathogenic Bacteria: A Review on Mechanisms and Recent Developments

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Abstract

Background: Antimicrobial resistance (AMR) is a global health crisis that is outpacing discovery of new antibiotics. Plant-derived phytochemicals and plant-based formulations are promising sources of novel antibacterial agents that may act by multiple mechanisms and restore antibiotic efficacy. **Objective:** To synthesize plant-derived antibacterials addressing (1) primary phytochemical classes, (2) Molecular and cellular mechanisms against pathogenic bacteria, (3) Evidence for synergy with conventional antibiotics, (4) Nanotechnology-based delivery/optimization strategies, and (5) Translational progress and barriers. **Methods:** A systematic literature search of Scopus (primary), complemented by PubMed and Web of Science, was performed for reviews and original research published mainly in the last decade. Search strings combined terms such as "plant antimicrobial", "phytochemical antibacterial", "antimicrobial resistance", "antibiofilm", "synergy antibiotic plant", and "nano-herbal". Peer-reviewed Scopus-indexed articles and high-quality reviews were prioritized for synthesis. **Results:** Major phytochemical groups (phenolics/flavonoids, alkaloids, terpenoids/essential oils, tannins, and saponins) exhibit antibacterial activity through membrane disruption, nucleic acid/protein synthesis inhibition, efflux pump modulation, quorum sensing (QS) interference and anti-biofilm effects. Synergistic combinations of plant extracts or phytochemicals with antibiotics restore activity against resistant strains in vitro. Nano-encapsulation and nano-emulsions substantially improve phytochemical stability and bioavailability. However, variability of extracts, and few clinical studies hinder translation. **Conclusion:** This review supports a strong preclinical rationale for plant-derived antibacterials as adjuncts or alternatives to antibiotics, particularly against biofilms and multidrug-resistant (MDR) pathogens. Focused standardization, mechanism-guided isolation, optimized delivery (nano-systems), and rigorous in vivo and clinical validation are required for clinical translation.

Keywords: Plant-derived antibacterials; Phytochemicals; Antimicrobial resistance (AMR); Synergy with antibiotics; Anti-biofilm; Nano-herbal formulations.

1. Introduction

Antimicrobial resistance (AMR) threatens modern medicine by undermining the effectiveness of standard antibiotics. The pipeline for new antibiotic classes is limited, and many pathogenic species—*Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Klebsiella pneumoniae*, *Enterococcus spp.* and Gram-negative Enterobacterales—exhibit multidrug resistance through diverse mechanisms (enzymatic degradation, efflux pumps, target modification, and biofilm formation)[1,2]. Plant secondary metabolites provide a structurally diverse reservoir of molecules historically used in traditional medicine and increasingly investigated in peer-reviewed Scopus sources for antibacterial potential. Plant compounds frequently act on multiple bacterial targets, a property that may reduce the rate of resistance emergence and provide synergistic opportunities when combined with conventional antibiotics. Recent Scopus-indexed reviews emphasize both mechanistic diversity and advances in delivery (including nano-formulations) that improve therapeutic potential[2,3].

2. Methods

2.1 Search strategy: Primary searches were executed in publications from 2010–2025.

2.2 Review criteria:

- Reviews and original research articles reporting antibacterial activity, mechanisms, synergy with antibiotics, nano-formulation of plant extracts or phytochemicals, and translational/clinical data.
- Human-pathogen focus (clinical isolates or clinically relevant strains).
- English language[4].

2.3 Extraction & synthesis: Extracted information included plant species, active phytochemicals, extraction methods, bacterial targets, MIC/MBC when available, proposed mechanisms, synergy data (checkerboard/FICI), anti-biofilm assays, and any in vivo/clinical data. Thematic synthesis grouped findings into (i) phytochemical classes/mechanisms, (ii) anti-biofilm and anti-virulence actions, (iii) synergy and efflux pump modulation, (iv) nano-formulations, and (v) translational evidence[4,5].

3. Results

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Detailed evaluations of multiple reviews: Extensive evaluation of plant-derived antibacterial agents over the past decade has revealed that multiple phytochemical classes contribute collectively to antimicrobial efficacy.

- Phenolics and flavonoids are among the most widely studied constituents, exhibiting strong activity against both Gram-positive and Gram-negative bacteria. These compounds primarily exert their effects through disruption of bacterial cell membranes, chelation of essential metal ions, and inhibition of key enzymes involved in nucleic acid and protein synthesis. Several in vitro investigations have demonstrated that flavonoids such as quercetin, kaempferol, and catechins increase membrane permeability, leading to leakage of intracellular contents and collapse of proton motive force. Additionally, phenolic acids have been reported to interfere with DNA gyrase and topoisomerase IV, thereby suppressing bacterial replication[6].
- Alkaloids represent another important class of antibacterial phytochemicals, acting mainly through intercalation into DNA and inhibition of RNA polymerase activity. Studies using isoquinoline and indole alkaloids have shown dose-dependent suppression of bacterial growth accompanied by morphological changes such as cell elongation and membrane distortion. Certain alkaloids also exhibit efflux pump inhibitory properties, which is particularly relevant in combating multidrug-resistant (MDR) strains. By blocking efflux transporters, these compounds increase intracellular accumulation of antibiotics, thereby restoring bacterial susceptibility[7].
- Terpenoids and essential oils demonstrate rapid bactericidal effects attri[7]buted largely to their lipophilic nature, enabling them to penetrate bacterial membranes and disrupt lipid bilayer integrity. Monoterpenes and sesquiterpenes have been shown to destabilize membrane proteins, impair ATP synthesis, and alter membrane fluidity. Essential oil components such as thymol, carvacrol, and eugenol additionally inhibit quorum sensing (QS) pathways, reducing bacterial virulence factor production and motility. This QS interference has been directly linked to diminished biofilm formation, a critical factor in persistent infections and antibiotic resistance.
- Tannins and saponins further contribute to antibacterial activity via distinct mechanisms. Tannins form irreversible complexes with bacterial cell wall proteins and extracellular enzymes, leading to growth inhibition and impaired nutrient uptake. Saponins, owing to their surfactant properties, interact with membrane sterols and phospholipids, resulting in pore formation and cytoplasmic leakage. Several

comparative studies indicate that crude extracts containing multiple phytochemical groups often display superior antibacterial activity compared to isolated constituents, suggesting additive or synergistic interactions among plant metabolites[8].

- A growing body of research highlights the capacity of plant extracts and purified phytochemicals to modulate bacterial resistance mechanisms. Anti-biofilm activity has been reported for numerous medicinal plants, with significant reductions observed in biofilm biomass, extracellular polymeric substance production, and surface adhesion. Microscopic analyses reveal disrupted biofilm architecture and increased susceptibility of embedded bacteria to conventional antibiotics. Moreover, phytochemicals targeting quorum sensing pathways effectively downregulate genes responsible for toxin production, adhesion, and biofilm maturation, offering a promising anti-virulence strategy that exerts less selective pressure for resistance development[9].
- Synergistic combinations of phytochemicals with standard antibiotics have emerged as a particularly impactful approach. Multiple in vitro checkerboard and time-kill assays demonstrate that plant-derived compounds significantly reduce the minimum inhibitory concentrations (MICs) of β-lactams, fluoroquinolones, aminoglycosides, and macrolides against resistant bacterial strains. Such combinations have been shown to reverse resistance phenotypes by enhancing membrane permeability, inhibiting efflux pumps, and suppressing resistance gene expression. These findings support the concept of phytochemical–antibiotic adjuvant therapy, wherein plant metabolites act as resistance-modifying agents rather than direct bactericidal drugs[10].
- Recent advances in nanotechnology have further amplified the therapeutic potential of plant-based antibacterials. Nano-encapsulation techniques, including polymeric nanoparticles, lipid-based carriers, and nano-emulsions, markedly improve the stability, solubility, and bioavailability of phytochemicals. Nano-formulated plant extracts demonstrate enhanced cellular uptake, sustained release profiles, and significantly lower MIC values compared to their conventional counterparts. Additionally, nanoparticle systems facilitate targeted delivery to infection sites and protect sensitive phytoconstituents from degradation. Several studies report superior anti-biofilm efficacy and prolonged antibacterial action using nano-herbal formulations, highlighting their relevance for chronic and resistant infections[10,11].

- Despite these encouraging results, substantial challenges remain in translating plant-based antibacterial agents from laboratory to clinic. Variability in phytochemical composition due to differences in plant species, geographical origin, harvesting conditions, and extraction methods leads to inconsistent biological activity. Lack of standardized extraction protocols and quality control measures further complicates reproducibility. Moreover, while numerous in vitro and limited in vivo studies validate antibacterial potential, well-designed clinical trials are scarce. Toxicological profiling, pharmacokinetic characterization, and regulatory frameworks for herbal and nano-herbal products also remain insufficiently developed[12].

Existing evidence underscores the multifaceted antibacterial mechanisms of plant-derived compounds, encompassing membrane disruption, inhibition of nucleic acid and protein synthesis, efflux pump modulation, quorum sensing interference, and anti-biofilm activity. The integration of phytochemicals with antibiotics and nanocarrier systems represents a promising strategy to overcome antimicrobial resistance. However, systematic standardization, mechanistic validation, and clinical evaluation are imperative to fully realize the translational potential of plant-based antibacterial therapeutics[9,12].

4. Discussion: The present synthesis highlights the substantial antibacterial potential of plant-derived phytochemicals against clinically relevant pathogens, particularly in the context of antimicrobial resistance (AMR). Unlike conventional antibiotics that typically act on a single molecular target, plant metabolites demonstrate multi-target activity involving membrane destabilization, inhibition of nucleic acid and protein synthesis, efflux pump modulation, quorum sensing suppression, and disruption of biofilm architecture. This mechanistic diversity provides a strong biological rationale for their effectiveness against multidrug-resistant (MDR) bacteria and supports their use as resistance-modifying agents[11].

- Phenolics, flavonoids, alkaloids, terpenoids, tannins, and saponins collectively contribute to antibacterial efficacy through complementary pathways. The ability of flavonoids and phenolic acids to interfere with DNA gyrase and topoisomerase IV mirrors the action of fluoroquinolones, while terpenoids and essential oils exert rapid bactericidal effects by compromising membrane integrity and cellular energetics. Importantly, several phytochemicals inhibit bacterial efflux pumps and quorum sensing systems, thereby attenuating virulence and restoring susceptibility to conventional antibiotics[8,11].

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- A key finding across Scopus-indexed studies is the consistent observation of synergy between plant compounds and antibiotics. Checkerboard and time-kill assays reveal significant reductions in MIC values when phytochemicals are combined with β-lactams, aminoglycosides, fluoroquinolones, and macrolides. These interactions appear to arise from enhanced membrane permeability, inhibition of resistance determinants, and suppression of biofilm-associated tolerance. Such results support the emerging paradigm of phytochemical–antibiotic adjuvant therapy, where plant metabolites enhance antibiotic efficacy rather than replacing existing drugs[9].
- Biofilm inhibition represents another clinically relevant advantage of plant-derived antibacterials. Biofilms protect bacteria from host immunity and antimicrobial agents, contributing to chronic and recurrent infections.
- The reviewed evidence demonstrates that multiple plant extracts and isolated compounds significantly reduce biofilm biomass, disrupt extracellular polymeric substances, and downregulate quorum sensing–regulated virulence genes. These antivirulence effects offer a promising strategy for managing persistent infections while minimizing selective pressure for resistance[5,8].
- Recent advances in nano-formulation technologies further strengthen the translational potential of plant-based antibacterials. Nano-encapsulation and nano-emulsion systems improve phytochemical solubility, stability, and bioavailability while enabling sustained release and targeted delivery. Nano-herbal formulations consistently exhibit enhanced antibacterial and anti-biofilm activity compared with crude extracts, highlighting the importance of optimized delivery systems in overcoming pharmacokinetic limitations of natural compounds[13].

5. Future Perspectives and Scopes:

Future research should prioritize mechanism-guided isolation of active phytochemicals, followed by standardized extraction and formulation protocols. Synergistic phytochemical–antibiotic combinations warrant systematic evaluation using clinically relevant MDR isolates and validated in vivo infection models. Particular emphasis should be placed on anti-biofilm strategies and efflux pump inhibition, given their relevance to persistent infections[11].

Nano-enabled delivery platforms offer substantial promise but require further optimization for safety, scalability, and regulatory acceptance. Rigorous pharmacokinetic, toxicological, and clinical investigations are essential to bridge the gap between laboratory findings and therapeutic application. Additionally, development of unified regulatory frameworks for plant-based and nano-herbal medicines will be critical for successful clinical translation[13].

Integration of computational modeling, systems biology, and artificial intelligence may further accelerate identification of lead phytochemicals and predict synergistic interactions. Ultimately, multidisciplinary collaboration among pharmacologists, microbiologists, formulation scientists, and clinicians will be central to advancing plant-derived antibacterials toward practical healthcare solutions.

6. Conclusion: This review provides comprehensive evidence that plant-derived antibacterial agents possess multifaceted mechanisms of action, including membrane disruption, inhibition of nucleic acid and protein synthesis, efflux pump modulation, quorum sensing interference, and anti-biofilm activity. Synergistic interactions with conventional antibiotics and advances in nano-formulation technologies substantially enhance their therapeutic potential, particularly against multidrug-resistant pathogens[14].

While current findings strongly support the preclinical promise of phytochemicals as adjuncts or alternatives to antibiotics, translation into clinical practice remains constrained by extract variability, limited in vivo validation, and scarcity of controlled clinical trials. Focused standardization, mechanism-driven development, optimized nano-delivery systems, and rigorous clinical evaluation are essential to fully realize the role of plant-based antibacterials in combating antimicrobial resistance[15].

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The Role of Inner Engineering in Promoting Sustainable Living and Holistic Wellbeing

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Abstract: Yoga is frequently viewed through the lens of physical fitness, yet it is fundamentally grounded in a philosophy of self-realization and internal transformation. Recent contemporary interpretations, notably "Inner Engineering" by Sadhguru, have reframed yoga as a sophisticated tool for recalibrating the internal dimensions of the human experience. This paper investigates the conceptualization of yoga as "inner engineering"—a systematic internal process aimed at optimizing the body, mind, emotions, and energies to facilitate holistic well-being. By synthesizing traditional yogic literature, empirical scientific data, and modern adaptations, this study provides a comprehensive analysis of yoga as a transformative technology for internal alignment and self-mastery. Yoga's identity as an "internal technology" is a systematization of ancient Vedic and post-Vedic wisdom. Vedic Foundations: The roots of yoga are found in the Vedas and Upanishads, which introduced concepts of Atman (self) and Brahman (universal consciousness) as the basis for spiritual pursuits. The Eightfold Path: Patanjali's Yoga Sutras systematized yoga into an eightfold path (Ashtanga Yoga), providing a step-by-step inner journey for self-discipline and enlightenment. Energy Mastery: Medieval traditions like Hatha and Tantra focused on mastery over internal energy systems, such as chakras and nadis, to awaken transformative forces like Kundalini.

Keyword: Inner Engineering, Holistic Well-being, Self-Mastery, Ashtanga Yoga, Neuroplasticity, Internal Alignment, Biopsychosocial Tuning, Shambhavi Mahamudra, Energy Systems (Chakras and Nadis), Yoga Psychology

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Introduction: The Mechanics of "Inner Engineering

The modern paradigm, popularized by Sadhguru, positions yoga as an internal technology designed to recalibrate the human landscape. The Engineering Analogy: In this model, the human system—body, mind, emotions, and energy—is viewed as a "machine," and yogic practices serve as the tools to optimize its function. Components of Alignment: Core practices like Shambhavi Mahamudra involve kriya, breath, and focus to create a "chemistry of blissfulness". Mind as a Tool: Yoga facilitates detachment from compulsive thoughts and improves cognitive clarity, paralleling self-regulation models in modern behavioral psychology. Contemporary research provides empirical evidence that yoga acts as a biopsychosocial tuning mechanism. Neurological Impact: Functional MRI studies show that meditation and pranayama increase grey matter in regions associated with attention and enhance connectivity between the prefrontal cortex and the limbic system. Psychological Benefits: Regular practice is linked to decreased cortisol levels, alleviating symptoms of anxiety and major depressive disorder. Physiological Balance: Breath regulation improves autonomic nervous system balance and enhances the parasympathetic "rest-and-digest" response. Yoga is increasingly integrated into rehabilitation and compared with conventional therapies. Comparison with CBT: Both yoga and Cognitive Behavioral Therapy aim to reprogram thought patterns, but yoga further addresses pre-verbal consciousness and subtle body energies. Neurofeedback: Meditation and breathwork are considered self-administered forms of neurofeedback because they naturally alter brainwave patterns. Rehabilitation Success: Qualitative feedback and case studies highlight yoga's efficacy in PTSD recovery, addiction treatment, and chronic pain management. The paper also addresses the limitations of framing yoga as a modern engineering product. Commercialization: Critics suggest that branding yoga as a self-help product may dilute its traditional spiritual depth. Scientific Challenges: Research is often hindered by a lack of standardization across different yoga schools and the influence of placebo effects. Integration over Escapism: The pursuit of "bliss" must be grounded in real-world integration rather than becoming a means of escaping life's complexities.

2. Historical and Philosophical Foundations of Yoga

2.1 Vedic Origins

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The roots of yoga can be traced back to the Vedas (1500–500 BCE), where early meditative practices and philosophical ideas about consciousness and union with the divine were introduced. The Upanishads elaborated on these ideas, discussing Atman (self) and Brahman (universal consciousness), forming the basis of yoga's spiritual pursuits.

2.2 The Yoga Sutras of Patanjali

Patanjali's Yoga Sutras (circa 400 CE) systematized yoga into an eightfold path (Ashtanga Yoga), outlining a comprehensive approach to self-discipline and enlightenment:

- Yama (ethical restraints)
- Niyama (observances)
- Asana (postures)
- Pranayama (breath control)
- Pratyahara (withdrawal of senses)
- Dharana (concentration)
- Dhyana (meditation)
- Samadhi (absorption)

This structure provides a step-by-step inner journey, strongly aligning with the concept of "inner engineering."

2.3 Hatha and Tantra Traditions

Medieval yoga traditions like Hatha Yoga and Tantra emphasized mastery over the body and energy systems (chakras, nadis). These methods aimed at awakening Kundalini energy, an inner transformative force.

3. Inner Engineering: A Modern Yogic Paradigm

3.1 What is Inner Engineering?

"Inner Engineering" is a term popularized by Sadhguru, a contemporary Indian yogi and founder of the Isha Foundation. According to him, it refers to:

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"A method of aligning your body, mind, emotions, and energies to function in harmony and produce a chemistry of blissfulness."

This model positions yoga not just as a practice but as an internal technology, much like engineering designs the external world, yoga engineers the inner landscape.

3.2 Components of Inner Engineering

- Shambhavi Mahamudra: A core practice in Inner Engineering that involves kriya (energy control), breath, and focus.
- Self-Inquiry: Participants engage in questions about the nature of the self and existence.
- Emotional Balance: Through yogic practices and awareness, practitioners are guided to transcend reactive emotional patterns.
- Neuroplasticity and Consciousness: Emerging research suggests these practices may reshape brain function and enhance emotional resilience.

4. Yoga as Inner Engineering: Conceptual Analysis

4.1 Definition of Engineering

Engineering typically involves designing, building, and optimizing systems. Translating this to yoga:

- The human system—body, mind, emotions, energy—is the "machine."
- Yogic practices serve as the design tools to recalibrate this machine.
- Optimal functioning of the system is the end goal.

4.2 Mind as a Tool

In both yogic thought and modern psychology, the mind is seen as a powerful but potentially unruly tool. Yoga offers:

- Detachment from compulsive thoughts (via meditation)
- Improved cognitive clarity (via mindfulness and breath control)

- Conscious choice-making, which parallels self-regulation models in behavioral psychology

5. Scientific Evidence Supporting Inner Transformation Through Yoga

5.1 Psychological Benefits

Numerous studies show that regular yoga practice:

- Reduces stress (decreased cortisol)
- Alleviates symptoms of anxiety and depression
- Enhances emotional regulation and empathy

Study Highlight:

- A meta-analysis published in Journal of Psychiatric Research (2016) confirmed yoga's efficacy in reducing symptoms of major depressive disorder, comparable to pharmacological interventions.

5.2 Neurological and Physiological Effects

Functional MRI studies show that meditation and breathing practices:

- Increase grey matter in regions associated with attention and compassion
- Enhance connectivity between prefrontal cortex and limbic system

Breath regulation (pranayama) has been shown to:

- Improve autonomic nervous system balance
- Enhance parasympathetic activity (rest-and-digest response)

These changes mirror system recalibrations, akin to tuning a machine—strengthening the argument that yoga acts as an internal engineering tool.

6. Energy Systems in Yoga

6.1 Chakras and Nadis

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Traditional yogic texts describe a system of energy centers (chakras) and channels (nadis). Though not measurable by current scientific tools, they align metaphorically with:

- Nervous system networks
- Hormonal and endocrine pathways

Practices like kundalini yoga, bandhas, and mudras aim to optimize energy flow—interpreted in modern terms as optimizing neuro-energetic functioning.

6.2 Inner Chemistry

The idea that inner experiences can produce distinct biochemical states (e.g., serotonin, oxytocin, dopamine) supports the premise that yoga alters our internal chemistry.

7. Comparative Perspectives

7.1 Yoga and Cognitive Behavioral Therapy (CBT)

- Both aim to reprogram thought patterns.
- Yoga goes further by addressing pre-verbal consciousness and subtle body energies.

7.2 Yoga and Neurofeedback

- Neurofeedback uses EEG to train brainwaves.
- Meditation and breathwork alter these same patterns—naturally and internally.

This supports the idea that yoga is a biopsychosocial tuning mechanism—a form of self-administered neuroengineering.

8. Case Studies and Testimonials

8.1 Inner Engineering Participants

Qualitative feedback from Inner Engineering participants indicates:

- Improved emotional stability
- Heightened focus and clarity
- Enhanced interpersonal relationships

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8.2 Rehabilitation and Recovery

Yoga is increasingly used in:

- PTSD recovery (e.g., veterans' programs)
- Addiction treatment
- Chronic pain management

These outcomes suggest deep internal recalibration, often achieved where conventional therapies fall short.

9. Criticisms and Limitations

9.1 Commercialization and Branding

Critics argue that concepts like "Inner Engineering" risk diluting the spiritual depth of yoga by branding it as a self-help product.

9.2 Lack of Standardization

Yoga's diverse schools mean not all practices yield the same outcomes. Scientific research struggles with:

- Variability in methodologies
- Placebo effects
- Cultural/contextual factors

9.3 Overemphasis on Bliss

The pursuit of bliss can become an escape from life's complexity. Yoga as inner engineering must be grounded in integration, not escapism.

10. Conclusion

Yoga, in its truest form, is far more than a set of postures. It is a system of self-regulation, transformation, and alignment—of engineering the internal systems of the human being toward optimal functioning. When viewed through this lens, the idea of "Inner Engineering"

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is not only philosophically sound but increasingly supported by neuroscience and psychological research.

By cultivating awareness, discipline, and inner balance, yoga becomes a technology for the self—a blueprint to engineer not machines, but meaning, peace, and purpose within.

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Student Enrollment in 7raj Air SQN NCC Air-Wing Session 2025-26: A Survey Report

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Abstract

The National Cadet Corps (NCC) plays a vital role in building discipline, leadership, and patriotism among youth while providing exposure to defense-oriented training. This study presents the findings of a survey conducted among university students enrolling in the NCC Air-Wing during the 2025–26 session. Data were collected through an online questionnaire and included responses from 105 students across diverse academic programs. The analysis focused on demographic characteristics, prior NCC experience, involvement in physical activities, and motivational factors influencing enrollment.

The results revealed that 72% of respondents were male and 28% female, reflecting a growing but still limited participation of women in NCC Air-Wing activities. A majority (83%) reported no previous NCC experience, highlighting the Air-Wing's role in introducing new cadets to the organization. While 59% of students actively engaged in sports or physical fitness, 41% indicated minimal or occasional activity, underlining the importance of structured physical training. Motivations for joining included aspirations for defense careers, development of leadership and discipline, opportunities for adventure, and inspiration from family traditions in the armed forces. The findings underscore the multifaceted appeal of NCC among students and emphasize the need for tailored training programs that combine physical, academic, and leadership development to maximize its impact.

Keywords: NCC, Air-Wing, University Students, Enrollment Survey, Defense Career Motivation, Physical Fitness, Discipline, Patriotism

1. INTRODUCTION

The National Cadet Corps (NCC) is one of the largest uniformed youth organizations in the world, established under the NCC Act of 1948 in India. Since its inception, NCC has aimed

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to instill values of discipline, leadership, unity, and patriotism among the youth while preparing them for constructive roles in society and potential careers in defense services. It functions as a voluntary tri-services organization, encompassing the Army, Navy, and Air-Wing. Among these, the Air-Wing holds a special place as it provides cadets with exposure to aviation-related knowledge, aeromodelling, flying experience, and defense orientation that align with India's growing aerospace and defense aspirations.

The importance of NCC extends beyond defense preparedness. It plays a crucial role in holistic development, offering young student's opportunities to engage in adventurous activities, social service, community development, and personality building. In recent years, the participation of university students in NCC has increased due to the recognition of its value in enhancing employability, discipline, and leadership qualities. The Air-Wing attracts students interested in aviation, the Air Force, and those motivated by patriotism and national service.

Youth participation in NCC is significant because it channels energy and enthusiasm towards productive endeavors. By joining NCC, students acquire life skills such as teamwork, resilience, and self-confidence. Moreover, it serves as a preparatory ground for those aspiring to join the armed forces while also benefiting others who wish to contribute to the nation through different sectors.

The purpose of this survey is to evaluate student enrollment in the NCC Air-Wing during the 2025–26 session. It aims to analyze demographic details, assess physical fitness involvement, and identify motivational factors behind participation. Such an evaluation is expected to provide insights that can guide program planning, recruitment strategies, and training interventions to maximize the benefits of NCC for students and the nation alike.

2. OBJECTIVES OF THE STUDY

1. To analyze enrollment demographics such as age, gender, and academic courses of applicants.
2. To identify reasons and motivations for students to join NCC Air-Wing.
3. To assess the level of student involvement in sports and physical activities.
4. To explore awareness and interest in defense careers among the enrolled students.

3. METHODOLOGY

This study adopted a survey-based descriptive research design to analyze the enrollment patterns of university students in the NCC Air-Wing during the 2025–26 session. A structured Google Form questionnaire was developed to collect responses from interested students. The

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questionnaire included sections on demographic details (age, gender, academic course), previous NCC experience, involvement in sports or physical activities, and motivational factors for joining NCC.

The survey was administered online, ensuring accessibility to students across different academic disciplines within the university. A total of 105 valid responses (N=105) were received and included in the analysis. Participation was voluntary, and students provided information with informed consent. Confidentiality of personal identifiers such as contact numbers and Aadhaar details was maintained, and only aggregated findings were reported.

Data collected were systematically coded and analyzed using basic statistical methods such as frequency counts and percentages. Results were represented in tables, bar charts, and pie diagrams to provide clarity on trends and patterns. Motivational responses were further categorized thematically into defense aspirations, personality development, adventure/experience, and family inspiration.

This methodological approach allowed for a comprehensive understanding of student enrollment trends, enabling insights into their physical readiness, career orientation, and underlying motivations for joining the NCC Air-Wing.

4. SURVEY DATA SEPARATION

- Total Respondents: 105 students (approx.).
- Gender Distribution:
  - Male: 76 (72%)
  - Female: 29 (28%)

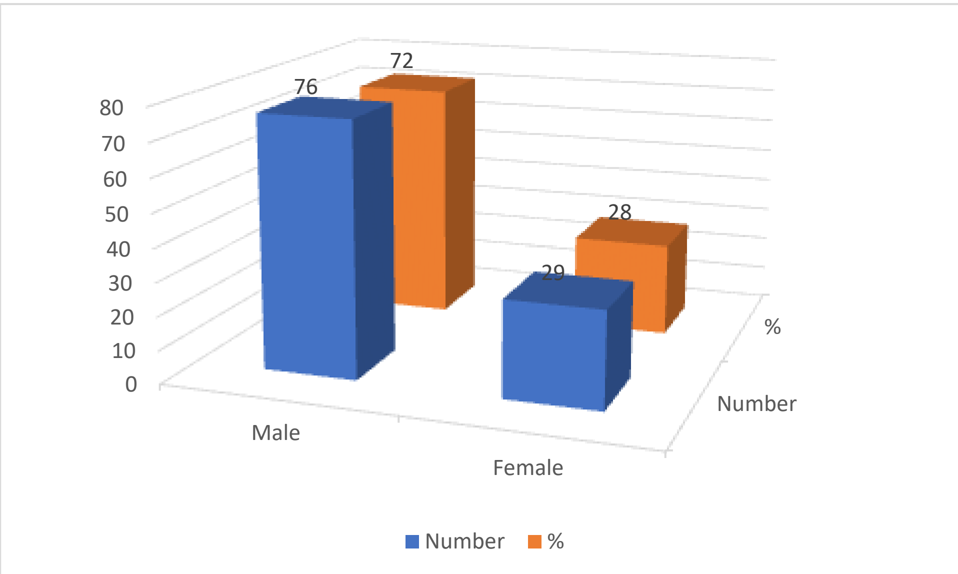

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Chart 1: Male vs Female Ratio participated in enrollment

- Previous NCC Experience:
    - No: 87 (83%)
    - Yes: 18 (17%)
- Involvement in Sports/Physical Activities:
    - Yes: 62 (59%)
    - No: 37 (35%)
    - Others (occasional/home workout): ~6%

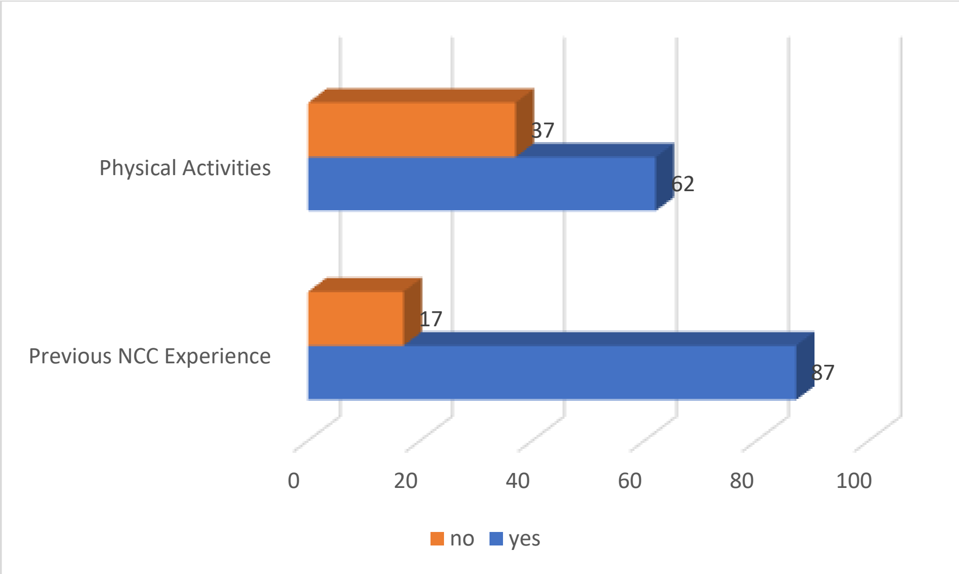

Chart 2: Physical participation and previous NCC experienced participated in enrollment

- Course Representation (top ones):
    - BBA: 12
    - BPT: 12
    - BCA: 6
    - BA LLB: 6
    - Others spread across ~60 courses.

The motivation to the students about NCC

- Defense Career & Patriotism: Many responses mention *Army, Airforce, CDS exam, Government jobs*.
- Personality Development & Discipline: Students highlighted *leadership, discipline, fitness, confidence*.

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- Adventure & Experience: Several noted *tracking, drills, adventurous activities*.
- Family Inspiration: Some mentioned parents/grandparents in Armed forces.

5. RESULTS AND DISCUSSION

A total of 105 students from the university participated in the survey for *NCC Air-Wing Enrollment Session 2025–26*. The analysis of their responses provides valuable insights into demographic profiles, prior NCC exposure, physical activity levels, and motivations for joining the program.

Demographic Profile: Out of the total respondents, 72% were male (n=76) and 28% were female (n=29). This indicates a higher inclination among male students towards NCC Air-Wing enrollment, though the female representation is also significant, highlighting a growing interest among women in defense-related activities.

Previous NCC Experience: Many applicants, 83% (n=87), reported no prior NCC experience, while 17% (n=18) had earlier exposure to NCC activities. This demonstrates that most candidates are new to the NCC system, making the Air-Wing an attractive entry point for fresh cadets.

Involvement in Physical Activities: A substantial proportion, 59% (n=62), reported active participation in sports or physical activities. Meanwhile, 35% (n=37) admitted to not being regularly engaged, and about 6% indicated occasional or home-based workouts. This shows that while many students already maintain physical fitness, a considerable segment requires structured training, which NCC can provide.

Course Representation: Students from diverse academic backgrounds applied. The top participating courses included BBA (12 students), BPT (12 students), BCA (6 students), and BA LLB (6 students). More than 60 other courses were represented, reflecting NCC's wide appeal across disciplines.

Motivations for Enrollment: Responses regarding motivations were diverse and were thematically categorized:

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1. Defense Career & Patriotism: Many respondents expressed aspirations to join the armed forces (Army, Airforce, Navy) or prepare for defense examinations such as CDS. Patriotism and national service were recurring themes.
2. Personality Development & Discipline: Several students cited the desire to develop qualities like *leadership, confidence, discipline, teamwork,* and *mental and physical fitness*.
3. Adventure & Experience: Several students were attracted by opportunities such as *drills, parades, trekking, and adventure activities*.
4. Family Inspiration: A few students mentioned being inspired by family members serving in the armed forces.

6. DISCUSSION

Complete session was supervised by Dr. Girish Kumar Vyas, Care taker officer of the NCC Air-wing. Twenty three cadets participated from 2^{nd} and 3^{rd} year of NCC for process this enrollment along with Cadet Under officer (Sajal Jain), Leading flying cadet (Bhooshan Sharma). The result indicates that the NCC Air-Wing attracts a broad spectrum of students, with defense career aspirations being the primary motivation. The relatively high participation of students without prior NCC experience underscores the need for effective orientation programs. Moreover, the interest shown by female students is noteworthy and reflects the inclusivity and evolving role of NCC in promoting gender equality in defense preparedness.

Physical activity trends highlight that while many students are already fit, NCC can play a crucial role in improving the fitness and discipline of those less active. The varied academic background of applicants indicates that NCC is perceived not only as a defense pathway but also as a platform for holistic personality development.

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Topical Herbal Gels for Acne Management: Formulation Approaches and Clinical Potential

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Abstract

Acne vulgaris is a chronic inflammatory disorder of the pilosebaceous unit that significantly affects quality of life and often requires long-term management. Conventional topical therapies such as antibiotics, retinoids, and benzoyl peroxide are effective but frequently associated with skin irritation, dryness, and development of microbial resistance. In recent years, topical herbal gels have emerged as promising alternatives owing to their multitarget therapeutic action and improved safety profiles. Herbal formulations contain diverse bioactive phytoconstituents that exhibit antibacterial, anti-inflammatory, antioxidant, and wound-healing properties, enabling simultaneous modulation of multiple acne-causing pathways. Gel-based delivery systems offer additional advantages, including non-greasy texture, enhanced skin penetration, localized drug action, and superior cosmetic acceptability. This review highlights recent advances in topical herbal gels for acne management, focusing on formulation approaches, key excipients, evaluation parameters, and clinical potential. Emphasis is placed on polymer selection, incorporation of herbal actives, physicochemical characterization, antimicrobial efficacy, and dermal safety. Clinical evidence suggests that herbal anti-acne gels effectively reduce inflammatory lesions, erythema, and bacterial load while demonstrating better tolerability than conventional synthetic formulations. Despite challenges related to extract standardization and stability, continued progress in formulation science is expected to strengthen their therapeutic utility. Overall, topical herbal gels represent a safe, patient-friendly, and effective strategy for long-term acne management.

Keywords: Topical herbal gels; Acne vulgaris; Phytoconstituents; Anti-acne formulation; Dermatological drug delivery

1. Introduction

Acne vulgaris is a multifactorial inflammatory disorder of the pilosebaceous unit characterized by excessive sebum secretion, follicular hyper-keratinization, microbial colonization, and inflammatory responses. It primarily affects adolescents and young adults; however, a significant number of individuals continue to experience acne into adulthood, often resulting in permanent scarring and considerable psychosocial impact, including reduced self-esteem and anxiety. The pathogenesis of acne involves complex interactions between hormonal imbalance, oxidative stress, bacterial proliferation, and immune dysregulation, making its management clinically challenging[1,2].

Conventional anti-acne therapies such as topical antibiotics, retinoids, and benzoyl peroxide remain the mainstay of treatment. Although these agents are effective in reducing inflammatory lesions and bacterial load, prolonged use is frequently associated with adverse effects including skin irritation, erythema, peeling, dryness, photosensitivity, and development of microbial resistance. These limitations often compromise patient adherence and highlight the need for safer, long-term therapeutic alternatives[2,3].

Herbal medicines have gained increasing attention in dermatological applications due to their broad spectrum of biological activities and improved safety profiles. Medicinal plants contain diverse bioactive constituents such as flavonoids, terpenoids, phenolic compounds, and alkaloids that act synergistically to exert antibacterial, anti-inflammatory, antioxidant, and wound-healing effects. Several herbal agents have demonstrated promising anti-acne potential by inhibiting acne-causing bacteria, reducing inflammation, regulating sebum production, and promoting skin repair. Unlike single-target synthetic drugs, herbal extracts offer multitarget action, which may enhance therapeutic efficacy while minimizing adverse reactions.

Among topical dosage forms, gel-based systems are particularly advantageous for acne management because of their non-greasy nature, rapid drug release, cooling sensation, ease of application, and superior cosmetic acceptability. Gels also provide enhanced skin penetration and localized delivery of active constituents with minimal systemic exposure. The incorporation of herbal extracts into topical gel formulations represents an effective integration of traditional medicinal knowledge with modern pharmaceutical technology. Such systems allow controlled delivery of phytoconstituents directly to affected skin layers, improving therapeutic outcomes while maintaining patient comfort[4,5].

Recent advances in polymer science, formulation strategies, and evaluation methodologies have further improved the stability, spreadability, and bioavailability of herbal gels.

Consequently, topical herbal gel formulations are emerging as promising alternatives to conventional acne therapies, offering safer and more patient-friendly options for long-term acne management[5].

2. Objective : The objective of this review is to summarize formulation approaches, polymer systems, evaluation parameters, and clinical potential of topical herbal gels used in acne management, highlighting their role as safer and effective alternatives to conventional treatments.

3. Rationale for Herbal Gels in Acne Management: Topical herbal gels are increasingly preferred in acne therapy because they offer localized treatment with superior cosmetic acceptability and improved patient comfort. Acne primarily affects superficial and deeper skin layers; therefore, topical delivery allows direct targeting of inflamed pilosebaceous units while minimizing systemic exposure. Gel-based systems provide a lightweight vehicle that facilitates rapid drug release and penetration, making them especially suitable for oily and acne-prone skin[6,7].

Herbal gels provide a multitarget therapeutic approach by simultaneously addressing microbial growth, inflammation, oxidative stress, and excessive sebum production. Medicinal plants contain diverse phytoconstituents such as flavonoids, terpenoids, phenolics, and alkaloids that exert antibacterial, anti-inflammatory, antioxidant, and wound-healing effects. Unlike synthetic agents that act on single pathways, herbal preparations offer synergistic action with improved tolerability, making them appropriate for long-term acne management[8].

Topical herbal gels are preferred in acne therapy due to:

- **Non-greasy and easily washable nature** – Gel formulations are water-based, leaving minimal residue on the skin and providing a cooling sensation that enhances comfort, particularly in inflamed acne lesions[7,8].
- **Enhanced patient compliance and cosmetic acceptance** – Their smooth texture, quick absorption, and absence of oiliness improve user satisfaction and encourage regular application during prolonged treatment.
- **Localized delivery of herbal actives** – Gels enable direct deposition of phytoconstituents at affected sites, increasing therapeutic efficiency while limiting systemic absorption[7,8].
- **Reduced risk of systemic side effects** – Since herbal gels act primarily at the application site, they minimize gastrointestinal and systemic adverse effects commonly associated with oral therapies[8].

- **Synergistic antimicrobial, anti-inflammatory, and antioxidant effects** – Multiple bioactive compounds work together to suppress acne-causing bacteria, reduce inflammatory mediators, neutralize free radicals, and promote skin repair[8,9].

Several herbal constituents exhibit sebostatic activity, helping regulate excessive sebum secretion, which is a major contributor to follicular blockage and bacterial proliferation. Gel matrices further enhance penetration of herbal actives into deeper skin layers while maintaining skin hydration and barrier function[8,9].

Overall, herbal gels target multiple acne-causing pathways simultaneously, including inhibition of *Cutibacterium acnes*, reduction of inflammation, modulation of oxidative stress, and regulation of sebaceous gland activity. This multifaceted mechanism, combined with superior safety and cosmetic acceptability, positions topical herbal gels as promising and patient-friendly alternatives to conventional anti-acne therapies.

4. Formulation Approaches for Herbal Anti-Acne Gels

Herbal anti-acne gels are commonly formulated by incorporating aqueous or hydroalcoholic plant extracts into suitable polymeric gel bases. The primary formulation objective is to achieve optimal viscosity, spreadability, stability, and skin compatibility while ensuring efficient delivery of herbal actives to the affected skin layers. Because acne-prone skin is generally oily and sensitive, gel systems are preferred over creams or ointments due to their lightweight texture, non-greasy nature, and enhanced patient acceptability[10,11].

The formulation strategy focuses on selecting compatible excipients that provide adequate structural integrity, promote uniform dispersion of herbal extracts, and maintain physicochemical stability throughout storage. Careful optimization of polymer concentration, extract loading, and auxiliary excipients is essential to avoid phase separation, precipitation of active constituents, or loss of therapeutic activity[11]. Additionally, pH adjustment is critical to ensure skin compatibility and prevent irritation. Some key formulation components are:-

- **Herbal Actives:** Plant extracts or essential oils serve as the primary therapeutic agents, offering antibacterial, anti-inflammatory, antioxidant, and wound-healing effects. These bioactive constituents help inhibit acne-causing bacteria, reduce erythema, control oxidative stress, and promote skin repair. Standardization of extracts is important to ensure consistent efficacy[11].
- **Gelling Agents:** Polymers such as Carbopol, hydroxypropyl methylcellulose, sodium alginate, and xanthan gum are employed to impart viscosity and structural stability to the formulation. These agents determine gel consistency, spreadability, and drug

release behavior. Proper polymer selection also influences skin feel and residence time on the application site[12].

- **Humectants:** Glycerin and propylene glycol are commonly incorporated to maintain skin hydration and prevent dryness associated with acne treatments. Humectants also improve gel texture and may assist in enhancing penetration of herbal actives by increasing skin hydration[13,14].
- **Preservatives:** Preservatives are added to prevent microbial contamination, particularly because herbal formulations are susceptible to microbial growth. Selection of appropriate preservatives ensures product safety and shelf stability without causing skin irritation.
- **Penetration Enhancers:** Natural oils, glycols, or mild surfactants are included to improve dermal absorption of phytoconstituents. These agents temporarily modify the stratum corneum barrier, facilitating deeper penetration of herbal actives while maintaining skin integrity[14].

Proper optimization of these components is crucial to achieve uniform drug distribution, appropriate rheological behavior, and long-term formulation stability. Factors such as polymer concentration, extract compatibility, and excipient interactions directly influence gel performance, therapeutic efficacy, and cosmetic acceptability[14,15]. When carefully designed, herbal anti-acne gels provide efficient localized delivery of phytoconstituents, improved patient compliance, and enhanced clinical outcomes.

5. Evaluation Parameters of Herbal Gels

Comprehensive evaluation of herbal anti-acne gels is essential to ensure formulation quality, safety, stability, and therapeutic effectiveness. These parameters help predict in-use performance and patient acceptability while supporting reproducibility during scale-up. Each evaluation test provides critical insight into physicochemical properties, drug release behavior, and skin compatibility[15].

- **Physical appearance and homogeneity** – The gel is visually examined for color, clarity, phase separation, and presence of particulate matter. Homogeneity ensures uniform distribution of herbal actives throughout the formulation, which is vital for consistent therapeutic action[16].
- **pH (skin-compatible range)** – The pH is measured to confirm compatibility with skin physiology, typically maintained between 5.5 and 7.0. Appropriate pH minimizes irritation and preserves stability of phytoconstituents.

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- **Viscosity and spreadability** – Viscosity determines gel consistency and ease of application, while spreadability reflects how uniformly the gel distributes over the skin. Optimal viscosity ensures adequate residence time at the application site, whereas good spreadability improves user comfort and drug coverage[17].
- **Drug content uniformity** – This parameter confirms even distribution of herbal actives within the gel matrix. Uniform drug content is essential to ensure reproducible dosing and therapeutic reliability[18].
- **In-vitro release studies** – These studies evaluate the rate and extent of herbal constituent release from the gel base, providing insight into diffusion behavior and predicting in-vivo performance. Release profiles also help optimize polymer concentration and formulation composition[17].
- **Antimicrobial activity** – The antibacterial efficacy of herbal gels is assessed against acne-associated microorganisms to confirm therapeutic potential. This test validates the biological activity of incorporated plant extracts.
- **Skin irritation testing** – Performed to assess dermal safety and biocompatibility. Herbal gels are expected to show minimal irritation, making this parameter especially important for long-term acne therapy[18].

These evaluation parameters provide a comprehensive understanding of formulation performance, stability, safety, and clinical suitability. Proper assessment ensures development of herbal gels that are not only therapeutically effective but also cosmetically acceptable and patient friendly.

6. Clinical Potential of Herbal Anti-Acne Gels

Clinical and experimental investigations have consistently demonstrated that topical herbal anti-acne gels effectively reduce inflammatory lesions, erythema, and microbial load while simultaneously improving overall skin texture and appearance. These formulations act through multiple mechanisms, including suppression of acne-causing bacteria, inhibition of inflammatory mediators, regulation of sebum secretion, and neutralization of oxidative stress. The presence of diverse phytoconstituents such as flavonoids, terpenoids, and phenolic compounds enables a synergistic therapeutic effect, allowing herbal gels to address several pathogenic factors of acne simultaneously[17,19].

Compared to conventional synthetic formulations, herbal gels generally exhibit superior tolerability with a lower incidence of adverse reactions such as dryness, peeling, burning sensation, and photosensitivity. This improved safety profile makes them particularly suitable

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for prolonged use, which is often required in chronic or recurrent acne. Patients with sensitive skin also benefit from herbal gels due to their soothing and skin-repairing properties, which help restore barrier function and reduce irritation[19].

Another important clinical advantage of herbal anti-acne gels is enhanced patient adherence. Their lightweight, non-greasy texture and cooling sensation improve cosmetic acceptability, encouraging regular application. Localized delivery of herbal actives minimizes systemic exposure while ensuring effective concentration at the site of action. Additionally, several herbal constituents promote wound healing and reduce post-inflammatory hyperpigmentation, contributing to better cosmetic outcomes and reduced risk of scarring[19].

The multitarget nature of herbal gels makes them particularly valuable in long-term acne management, where monotherapy with synthetic agents may lead to resistance or intolerance. With continued improvements in formulation technology and growing clinical evidence, topical herbal gels are increasingly recognized as safe, effective, and patient-friendly alternatives or adjuncts to conventional anti-acne therapies.

7. Challenges and Limitations: Despite promising outcomes, herbal gel development faces challenges such as:

- Variability in herbal extract composition
- Standardization of active markers
- Stability issues of phytoconstituents
- Limited large-scale clinical data

Addressing these limitations requires robust quality control, advanced analytical techniques, and well-designed clinical trials[18-20].

8. Future Perspectives: Emerging technologies such as nano-herbal gels, bioadhesive systems, and quality-by-design approaches are expected to enhance stability and skin penetration of herbal actives. Integration of modern formulation science with traditional medicinal knowledge will further strengthen the therapeutic potential of topical herbal gels.

9. Conclusion: Topical herbal gels represent a promising, patient-friendly approach for acne management by combining the therapeutic benefits of medicinal plants with modern gel-based delivery systems. Advances in polymer technology and formulation strategies have enabled development of stable, effective, and cosmetically acceptable products. Although challenges related to standardization and clinical validation remain, continued research is likely to establish herbal gels as reliable alternatives to conventional anti-acne therapies, offering safer long-term management of acne vulgaris.

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Sustained-Release Transdermal Systems for NSAIDS in Musculoskeletal Pain Management

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Abstract:

Musculoskeletal pain associated with conditions such as arthritis, muscle strain, and sports injuries represents a major cause of disability worldwide and is commonly managed using non-steroidal anti-inflammatory drugs (NSAIDs). However, long-term oral administration of NSAIDs is frequently limited by gastrointestinal irritation, cardiovascular risks, and fluctuating plasma drug levels. Sustained-release transdermal drug delivery systems (TDDS) have emerged as a promising alternative by providing controlled drug release through the skin, bypassing hepatic first-pass metabolism and improving patient compliance. This review summarizes recent advances in sustained-release transdermal NSAID systems for musculoskeletal pain management, with emphasis on formulation design strategies, polymer selection, the role of pressure-sensitive adhesives (PSAs), and in-vitro evaluation methodologies. Key aspects such as matrix and drug-in-adhesive patch designs, polymeric matrices, permeation enhancement approaches, and mechanical performance parameters are discussed. In-vitro and ex-vivo studies demonstrate that optimized transdermal patches can maintain therapeutic drug levels for up to 24 hours, offering continuous analgesic and anti-inflammatory effects while reducing dosing frequency. Clinically, transdermal NSAID delivery provides improved tolerability, reduced gastrointestinal exposure, and enhanced patient adherence, particularly in chronic conditions requiring prolonged therapy. Although challenges related to stability, large-scale manufacturing, and regulatory acceptance persist, ongoing innovations in polymer science and formulation technology are expected to accelerate clinical translation. Sustained-release NSAID transdermal systems therefore represent a patient-friendly and effective alternative to conventional oral therapy for long-term musculoskeletal pain management.

Keywords: Sustained-release transdermal patches; NSAIDs; Musculoskeletal pain; Pressure-sensitive adhesives; Polymeric drug delivery systems.

1. Introduction

Musculoskeletal pain represents one of the most common causes of physical disability worldwide and is frequently associated with conditions such as osteoarthritis, rheumatoid arthritis, muscle strain, sports injuries, and lower back pain[1]. These disorders significantly impair mobility and quality of life, particularly among elderly and working populations. Non-steroidal anti-inflammatory drugs (NSAIDs) remain the cornerstone of pharmacological management due to their combined analgesic and anti-inflammatory properties. However, conventional oral administration of NSAIDs is often accompanied by gastrointestinal irritation, ulceration, renal impairment, cardiovascular risks, and fluctuating plasma drug levels, especially during long-term therapy. To overcome these limitations, sustained-release transdermal drug delivery systems (TDDS) have gained increasing attention as an alternative route for NSAID administration[2]. Transdermal delivery allows drugs to permeate through the skin directly into systemic circulation, thereby bypassing hepatic first-pass metabolism and minimizing gastrointestinal exposure. This approach enables controlled and prolonged drug release, maintains steady plasma concentrations, reduces dosing frequency, and improves patient adherence through non-invasive application. Moreover, localized delivery to affected tissues may further enhance therapeutic outcomes while limiting systemic toxicity[2,3].

Recent advances in polymer science, pressure-sensitive adhesive (PSA) technology, and formulation strategies have significantly improved the feasibility of sustained-release NSAID transdermal patches. Modern systems are designed to provide consistent drug flux over 24 hours or longer, ensuring continuous pain relief and better compliance in chronic musculoskeletal conditions. The incorporation of suitable polymers, permeation enhancers, and optimized PSA matrices has enabled improved mechanical stability, adhesion, and predictable drug release profiles[3,4]. Sustained-release transdermal NSAID systems are

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emerging as promising alternatives to conventional oral therapy for musculoskeletal pain management. Ongoing research focuses on refining patch design, enhancing skin permeation, and establishing robust in-vitro evaluation models to support clinical translation. This growing body of work highlights the potential of transdermal technology to deliver safer, more effective, and patient-friendly pain management solutions[5].

2. Objective of the Review

The objective of this review is to summarize recent advances in sustained-release transdermal systems for NSAIDs used in musculoskeletal pain management, with emphasis on formulation design strategies, polymer selection, the role of pressure-sensitive adhesives (PSAs), in-vitro evaluation methods, and overall therapeutic outcomes.

3. Need of the Study: Conventional oral NSAID therapy often requires repeated dosing and is associated with dose-related adverse effects. Sustained-release transdermal systems address these limitations by:

- Providing prolonged and controlled drug delivery
- Reducing gastrointestinal exposure
- Maintaining uniform plasma drug levels
- Enhancing patient adherence through non-invasive application
- Enabling localized or systemic analgesic and anti-inflammatory action

Given the chronic nature of many musculoskeletal disorders, development of reliable transdermal NSAID platforms is clinically significant for long-term pain management.

4. Design Strategies for Sustained-Release NSAID Patches: Modern NSAID transdermal patches are commonly formulated as matrix systems, drug-in-adhesive systems, or reservoir-type patches, each designed to provide controlled and sustained drug delivery. The primary formulation objective is to achieve predictable release kinetics while maintaining adequate skin compatibility, mechanical strength, and patient comfort[6]. Design strategies emphasize optimization of polymeric matrices, adhesive performance, and drug distribution to ensure consistent therapeutic outcomes. Main formulation consideration includes:

- Selection of polymers with appropriate film-forming and release properties – Polymers must provide sufficient mechanical integrity while allowing controlled diffusion of NSAIDs across the skin.
- Optimization of drug loading to prevent crystallization – Excess drug concentration may lead to crystallization within the matrix, negatively affecting release uniformity and bioavailability[7].

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- Incorporation of permeation enhancers to improve skin flux – Enhancers temporarily alter stratum corneum structure, facilitating increased transdermal permeation of NSAIDs.
- Use of plasticizers for flexibility and comfort – Plasticizers such as glycerol or polyethylene glycol reduce brittleness, improve patch elasticity, and enhance patient comfort during prolonged wear[7,8].

In addition, formulation development involves regulating patch thickness, polymer ratios, and drug–polymer interactions to control diffusion pathways. Uniform drug distribution, adequate adhesive strength, and moisture balance are also critical parameters influencing patch performance. Controlled release is achieved primarily by modifying polymer composition, matrix density, and interfacial interactions between the drug and carrier system. Collectively, these strategies enable the development of sustained-release transdermal patches capable of delivering NSAIDs effectively while ensuring stability, comfort, and therapeutic reliability[6-8].

5. Role of Polymers and Pressure-Sensitive Adhesives (PSAs): Polymers constitute the structural foundation of transdermal patches and play a decisive role in determining mechanical strength, flexibility, and drug diffusion characteristics.

- Commonly employed polymers such as hydroxypropyl methylcellulose, polyvinyl alcohol, ethyl cellulose, Eudragit®, and polyvinylpyrrolidone are favored for their reproducible quality, excellent film-forming ability, and controlled release properties[9].
- These polymers enable precise modulation of NSAID release profiles while ensuring adequate patch integrity and patient comfort. Strategic blending of polymers is often used to optimize elasticity, moisture resistance, and permeation behavior, thereby enhancing overall formulation performance[9,10].
- Pressure-sensitive adhesives (PSAs) perform a dual function by securing the patch to the skin and, in drug-in-adhesive systems, serving as the primary drug-containing matrix. Acrylic, silicone, and rubber-based PSAs are most utilized due to their favorable adhesion properties and chemical stability.
- An ideal PSA should provide consistent adhesion throughout the application period, exhibit compatibility with NSAIDs and other excipients, and allow uniform drug diffusion without compromising skin integrity[10].

PSAs must maintain adhesive performance under varying physiological conditions while minimizing the risk of irritation or sensitization. Proper selection and optimization of

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polymers and PSAs are therefore critical to achieving sustained drug release, reliable adhesion, and improved therapeutic efficacy in transdermal NSAID delivery systems.

6. In-Vitro Evaluation of Sustained-Release NSAID Patches: Comprehensive in-vitro evaluation is a critical step in the development of sustained-release transdermal NSAID patches, as it provides essential information regarding formulation quality, release behavior, and predicted clinical performance. These studies help optimize formulation variables and ensure reproducibility before in-vivo investigations[11]. Main In-Vitro Evaluation Parameters are

- **Physical characterization:** Thickness, weight variation, folding endurance, flatness, and surface pH are measured to confirm uniformity, mechanical integrity, and skin compatibility.
- **Mechanical properties:** Tensile strength and percentage elongation are evaluated to assess patch durability and flexibility during prolonged application.
- **Drug content uniformity:** Ensures homogeneous distribution of NSAIDs within the patch matrix[12].
- **Moisture uptake and loss:** Determines formulation stability under varying humidity conditions.
- **In-vitro drug release studies:** Conducted using diffusion cells to characterize sustained-release behavior over extended periods.
- **Ex-vivo skin permeation analysis:** Performed using Franz diffusion cells to estimate drug flux and predict in-vivo transdermal performance[13].
- **Release kinetics modeling:** Drug release data are fitted to zero-order, Higuchi, and Korsmeyer–Peppas models to elucidate the mechanism of release[13,14].

These evaluations provide critical insight into formulation performance, allowing optimization of polymer concentration, patch thickness, and permeation enhancer levels while ensuring batch-to-batch consistency and clinical relevance.

7. Results and Clinical Relevance

Numerous formulation and in-vitro studies have demonstrated that sustained-release transdermal NSAID systems can maintain therapeutically effective plasma drug concentrations for up to 24 hours or longer, thereby significantly reducing dosing frequency while providing continuous analgesic and anti-inflammatory effects.

- ➢ Optimized transdermal patches exhibit controlled release profiles, satisfactory mechanical properties, and enhanced skin permeation, supporting their potential for

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long-term clinical use. In-vitro and ex-vivo permeation studies consistently report improved drug flux and sustained delivery when appropriate polymers, penetration enhancers, and pressure-sensitive adhesives are employed[15].

- From a clinical perspective, transdermal NSAID delivery offers distinct advantages over conventional oral therapy, including reduced gastrointestinal irritation, avoidance of hepatic first-pass metabolism, and improved tolerability[15,16].
- These benefits translate into enhanced patient compliance, particularly among elderly individuals and patients with chronic musculoskeletal disorders who require prolonged pain management. Additionally, localized drug delivery to affected tissues may further enhance therapeutic outcomes while minimizing systemic exposure[16].

8. Conclusion: Sustained-release transdermal systems represent a promising platform for NSAID delivery in musculoskeletal pain management. Advances in polymer science, PSA technology, and formulation optimization have enabled the development of patches with predictable release profiles and satisfactory skin compatibility. Although challenges related to long-term adhesion, large-scale manufacturing, and regulatory harmonization remain, continued research and quality-by-design approaches are expected to further enhance clinical acceptance. With ongoing innovation, NSAID transdermal patches have strong potential to become reliable, patient-friendly alternatives to conventional oral therapy.

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Advances in Herbal Transdermal Patches for Chronic Inflammation Management

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Abstract

Long-standing inflammatory conditions such as arthritis, muscular pain, and connective tissue disorders require prolonged treatment, where conventional oral therapy often leads to gastrointestinal disturbances, fluctuating drug levels, and reduced patient compliance. Herbal medicines possess multi-component anti-inflammatory activity and are generally associated with fewer adverse effects. Incorporation of herbal actives into transdermal drug delivery systems offers a promising alternative by providing sustained drug release, avoiding hepatic first-pass metabolism, and enhancing therapeutic consistency. Recent pharmaceutical developments have emphasized the use of advanced polymers, permeation enhancers, and optimized evaluation strategies to improve the performance of herbal transdermal patches. This review summarizes current progress in herbal transdermal patch technology for chronic inflammation, highlighting formulation components, penetration enhancement techniques, evaluation parameters, stability considerations, existing challenges, and future research directions.

Keywords: Herbal transdermal patches; Chronic inflammation; Penetration enhancers; Polymeric drug delivery; Phytoconstituents

1. Introduction: Chronic inflammation is a persistent pathological condition characterized by continuous activation of immune responses and excessive production of inflammatory mediators, which may ultimately lead to tissue damage, fibrosis, and loss of physiological function. It plays a central role in the progression of several disorders including arthritis, musculoskeletal pain, cardiovascular diseases, and autoimmune conditions[1,2].

- Conventional anti-inflammatory therapy mainly relies on synthetic agents such as non-steroidal anti-inflammatory drugs (NSAIDs) and corticosteroids. Although these drugs provide effective symptomatic relief, prolonged administration is often associated with adverse effects including gastrointestinal irritation, renal impairment, cardiovascular risks, and reduced patient compliance[1].

- Herbal therapeutics have emerged as promising alternatives owing to their multi-target mechanisms of action and comparatively better safety profiles. Medicinal plants contain diverse bioactive constituents such as flavonoids, terpenoids, alkaloids, and phenolic compounds that act synergistically to suppress inflammatory pathways, inhibit oxidative stress, and modulate immune responses[2].
- Unlike single-molecule synthetic drugs, herbal extracts exert therapeutic effects through multiple biochemical targets, which may enhance efficacy while minimizing toxicity. Consequently, interest in herbal-based formulations for chronic inflammatory conditions has increased substantially in recent years[2,3].
- Transdermal drug delivery systems represent an advanced pharmaceutical approach that allows drugs to be administered across the skin directly into systemic circulation. This route offers several advantages, including avoidance of hepatic first-pass metabolism, sustained plasma drug levels, reduced dosing frequency, and improved patient adherence[3].
- Additionally, transdermal delivery minimizes gastrointestinal exposure and is particularly beneficial for patients requiring long-term therapy. The use of transdermal patches enables controlled release of active compounds over extended periods, thereby maintaining consistent therapeutic concentrations[3,4].
- The incorporation of herbal extracts into transdermal patches combines the benefits of traditional medicine with modern drug delivery technology. Herbal transdermal patches provide localized or systemic anti-inflammatory effects while reducing systemic side effects commonly associated with oral medications.

Advances in polymer science, penetration enhancement techniques, and formulation optimization have significantly improved the permeability of phytoconstituents through the stratum corneum. As a result, herbal transdermal systems are increasingly explored as viable alternatives for chronic inflammation management[4].

2. Objective: The primary objective of this review is to compile and analyze recent advancements in herbal transdermal patch formulations for chronic inflammatory conditions, with special emphasis on polymer selection, penetration enhancers, evaluation methodologies, stability assessment etc. which provides a comprehensive reference for researchers.

3. Importance of Herbal Transdermal Delivery in Chronic Inflammation: Herbal transdermal drug delivery offers an effective alternative to oral therapy by providing sustained release of bioactive phytoconstituents while bypassing hepatic first-pass metabolism. This approach enhances therapeutic bioavailability, maintains consistent plasma drug levels, and reduces gastrointestinal adverse effects[4]. Furthermore, transdermal systems improve patient compliance through non-invasive administration and are particularly beneficial for long-term management of chronic inflammatory conditions. The advantages are given below:

- Avoids first-pass metabolism and gastrointestinal degradation.
- Provides controlled and prolonged drug release.
- Enhances bioavailability of poorly soluble herbal constituents.
- Reduces dosing frequency and systemic side effects.
- Improves patient adherence due to painless application.
- Enables localized or systemic anti-inflammatory action.
- Suitable for long-term therapy in chronic inflammatory disorders[5].

4. Polymers in Herbal Transdermal Patch Formulation

Polymers constitute the structural framework of transdermal patches and play a critical role in determining film-forming ability, mechanical strength, drug release kinetics, and skin adhesion. The selection of an appropriate polymer directly influences patch flexibility, stability, and permeation characteristics. Both natural and synthetic polymers are widely employed either alone or in combination to achieve optimal therapeutic performance[6].

4.1 Natural Polymers: Natural polymers such as chitosan, sodium alginate, gelatin, and cellulose derivatives are preferred for their biocompatibility, biodegradability, and minimal toxicity. These polymers also exhibit favorable swelling properties that support drug diffusion. However, inherent variability in plant or animal sources, limited mechanical strength, and susceptibility to microbial growth may restrict their independent use. Consequently, natural polymers are often blended with synthetic counterparts to enhance film durability and consistency[7,8].

4.2 Synthetic and Semi-Synthetic Polymers: Synthetic and semi-synthetic polymers including hydroxypropyl methylcellulose, polyvinyl alcohol, ethyl cellulose, Eudragit, and polyvinylpyrrolidone are extensively utilized due to their reproducible quality, superior film-forming capacity, and predictable drug release behavior. These polymers provide excellent mechanical integrity and allow precise control over release profiles.

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Polymer blends are commonly optimized to balance elasticity, tensile strength, moisture resistance, and permeation properties, thereby improving patch performance and patient comfort. The rational selection and combination of polymers remain a key strategy in developing effective herbal transdermal delivery systems[7,8].

5. Penetration Enhancers: The stratum corneum acts as the primary barrier to transdermal drug permeation, significantly limiting the transport of herbal phytoconstituents across the skin. To overcome this limitation, penetration enhancers are incorporated into patch formulations to temporarily modify skin permeability. Commonly used enhancers include terpenes, fatty acids, alcohols, surfactants, and essential oils[9]. These agents enhance drug flux by disrupting the lipid organization of the stratum corneum, increasing skin hydration, and improving the solubility and partitioning of herbal actives within epidermal layers. The selection of an appropriate enhancer is critical, as it must provide effective permeation while maintaining skin integrity and minimizing irritation. Natural enhancers are increasingly preferred due to their biocompatibility and reduced risk of adverse skin reactions[9,10].

6. Evaluation Parameters of Herbal Transdermal Patches

Comprehensive evaluation is essential to ensure the quality, safety, and therapeutic reliability of herbal transdermal patches. Common assessment parameters include physical characteristics such as thickness, weight uniformity, folding endurance, flatness, and surface pH, which indicate formulation consistency and user comfort. Mechanical properties including tensile strength and percentage elongation are measured to determine patch durability and flexibility during application[11].

- Additional evaluations involve drug content uniformity, moisture uptake and loss, and adhesive properties to confirm stability under storage conditions.
- In-vitro drug release studies and ex-vivo skin permeation analysis using diffusion cells are performed to predict release behavior and permeation efficiency, while skin irritation tests assess biocompatibility[11,12].
- Collectively, these parameters provide critical insight into formulation performance, stability, and clinical suitability.

7. Stability Studies: Stability testing is performed in accordance with International Council for Harmonisation of Technical Requirements for Pharmaceuticals for Human Use (ICH) guidelines to evaluate changes in physical appearance, drug content, adhesive properties, and release characteristics over time[13].

- Herbal transdermal patches are typically subjected to accelerated stability conditions (40 ± 2 °C / 75 ± 5% RH) for up to 3–6 months, along with long-term storage conditions (25 ± 2 °C / 60 ± 5% RH) for extended evaluation. Parameters such as patch integrity, color, flexibility, drug content uniformity, and in-vitro release profiles are periodically assessed[13].
- Herbal formulations require special consideration because phytoconstituents are highly sensitive to environmental factors such as heat, moisture, oxygen, and light, which may lead to degradation or loss of therapeutic potency. Studies have shown that unacceptable changes in drug content or mechanical properties can occur if patches are not adequately protected from humidity.
- Therefore, moisture-resistant packaging materials (such as aluminum foil pouches or laminated sachets) and the incorporation of antioxidants or stabilizing agents are often employed to maintain formulation integrity[13,14].
- A product is generally considered stable when it retains 90–110% of its initial drug content and exhibits no significant changes in physical or release characteristics throughout the testing period[14].

8. Challenges in Developing Herbal Transdermal Patches

The development of herbal transdermal patches is constrained by several scientific and technical limitations, including variability in herbal extract composition and poor skin permeability of high-molecular-weight phytoconstituents. Difficulties in standardization and quality control further affect formulation reproducibility. In addition, potential skin irritation from penetration enhancers and the lack of specific regulatory guidelines complicate clinical translation and large-scale manufacturing[15,16]. Some challenges are being faced by researchers outlined below:

- Batch-to-batch variation in herbal extracts.
- Limited permeation of large or hydrophilic phytochemicals.
- Difficulty in standardization and marker compound identification.
- Risk of skin irritation or sensitization from enhancers.
- Stability issues due to sensitivity of phytoconstituents.
- Scale-up and manufacturing consistency.
- Absence of harmonized regulatory frameworks for herbal TDDS[15,16].

9. Conclusion and Future Perspectives

Herbal transdermal patches represent a promising and patient-friendly therapeutic approach for the management of chronic inflammatory disorders by integrating the pharmacological potential of medicinal plants with advanced controlled drug delivery technologies. Recent progress in polymer science, penetration enhancement strategies, and evaluation methodologies has significantly improved formulation performance and therapeutic outcomes. Emerging approaches such as nano-carrier incorporation, microneedle-assisted delivery, and smart polymer systems are expected to further enhance skin permeation and drug stability. However, challenges related to extract standardization, large-scale manufacturing, and regulatory acceptance remain. The adoption of quality-by-design principles, advanced analytical techniques, and interdisciplinary research efforts will be essential to overcome these limitations. With continued scientific validation and regulatory harmonization, herbal transdermal patches have the potential to evolve into reliable clinical alternatives for long-term inflammation management.

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Soil pH as a Master Variable: Implications for Soil Fertility and Crop Productivity – A Review

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Abstract

Soil pH is widely recognized as a "master variable" that regulates a broad range of chemical, biological, and physical processes in soils, thereby exerting a strong influence on soil fertility and crop productivity. This review synthesizes current knowledge on the role of soil pH in controlling nutrient availability, microbial activity, root growth, and overall plant performance, with particular emphasis on its implications for sustainable agricultural management. Evidence from field and laboratory studies demonstrates that soil pH governs the solubility and chemical forms of essential macro- and micronutrients, influences the activity and composition of soil microbial communities, and affects soil buffering capacity and biogeochemical cycling. Acidic soils are often constrained by aluminium and manganese toxicity and reduced availability of base cations, whereas alkaline soils commonly suffer from micronutrient deficiencies and phosphorus fixation. In contrast, neutral to slightly acidic soils generally provide optimal conditions for nutrient uptake, microbial functioning, and root development, resulting in improved crop growth and yield. The review further discusses factors controlling soil pH, including parent material, climate, biological processes, and management practices, and evaluates key strategies for pH management such as liming, organic amendments, acidifying inputs, and precision soil testing. Finally, emerging research directions, including site-specific pH management and integration with climate-smart agriculture, are highlighted. Overall, maintaining soil pH within an optimal

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range is fundamental for enhancing nutrient use efficiency, sustaining soil health, and achieving long-term agricultural productivity.

Keywords: Soil pH, Soil Fertility, Crop Productivity, Nutrient Availability, Soil Chemistry, Microbial Activity, Soil Health, pH Management, Agricultural Sustainability, Soil–Plant Interaction

1. Introduction

Soil pH is a critical factor influencing soil health, plant growth, and overall agricultural productivity. It refers to the degree of acidity or alkalinity of the soil and is widely regarded as a **"master variable"** because it regulates numerous physical, chemical, and biological processes in the soil system. Soil pH is measured on a logarithmic scale ranging from 0 to 14, where values below 7 indicate acidic soils, values above 7 indicate alkaline soils, and values around 7 represent neutral conditions. This single parameter exerts a strong control over nutrient availability, microbial activity, enzymatic reactions, and plant root development, thereby directly affecting soil fertility and crop performance [1,4]. The pH of soil strongly influences the solubility and mobility of essential plant nutrients, which in turn determines their uptake by crops. In addition, soil pH plays a vital role in shaping the composition and activity of soil microbial communities, which are responsible for organic matter decomposition, nutrient mineralization, and biogeochemical cycling [1,2]. Therefore, soil pH serves as a central regulator of soil ecosystem functioning and agricultural sustainability. In agricultural practice, understanding and managing soil pH is fundamental for ensuring healthy plant growth and optimizing crop yields. Most agricultural crops perform best in neutral to slightly acidic soils (pH 6.0–7.0); however, several crops have specific pH requirements. For instance, crops such as blueberry prefer strongly acidic soils, whereas asparagus and some legumes grow better under slightly alkaline conditions [3,4]. This crop-specific response to soil pH highlights the importance of proper pH management in achieving maximum productivity and maintaining soil health.

Soil pH also has a profound effect on nutrient availability and potential toxicity. In acidic soils, elements such as iron (Fe), manganese (Mn), and aluminum (Al) become more soluble, which

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may lead to toxicity and restricted root growth. Conversely, in alkaline soils, the availability of nutrients such as iron, zinc (Zn), and phosphorus (P) is reduced due to precipitation and fixation reactions, often resulting in nutrient deficiency symptoms in crops [2,5]. Hence, maintaining soil pH within an optimum range is essential to avoid nutrient imbalances, enhance nutrient use efficiency, and improve crop productivity. In this context, soil pH truly functions as a master variable governing soil fertility and agricultural performance.

2. Fundamentals of Soil pH

Soil pH is a measure of the hydrogen ion (H^+) concentration in the soil solution and serves as an indicator of soil acidity or alkalinity. It plays a fundamental role in determining soil chemical reactions, nutrient transformations, microbial activity, and the overall health of the soil ecosystem. Because many soil processes are pH-dependent, even small changes in soil pH can lead to significant alterations in nutrient availability and biological activity [1,2]. Soil pH is commonly measured using a pH meter in a soil–water or soil–salt (e.g., $CaCl_2$) suspension. The measured value reflects the intensity of soil acidity or alkalinity and provides a practical basis for making soil management decisions, such as liming acidic soils or applying acidifying amendments to alkaline soils. The natural pH of soils is influenced by several factors, including parent material, climate, vegetation, topography, and land-use practices. In humid regions, soils tend to become more acidic due to leaching of basic cations, whereas in arid and semi-arid regions, soils often become alkaline because of the accumulation of calcium, magnesium, and sodium salts [3,5]. Various soil processes contribute to pH variation over time, including organic matter decomposition, nitrification, root exudation, fertilizer application, and irrigation water quality. For example, the use of ammonium-based fertilizers promotes soil acidification through nitrification, while the application of lime increases soil pH by neutralizing hydrogen and aluminum ions in the soil exchange complex [1,4]. These dynamic processes demonstrate that soil pH is not a static property but a manageable factor that can be manipulated to improve soil fertility and crop productivity. Thus, understanding the fundamentals of soil pH is essential for sustainable soil management, as it provides the scientific basis for correcting soil constraints, improving nutrient availability, and enhancing crop performance. Given its central role in

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controlling soil chemical and biological processes, soil pH justifiably deserves recognition as a master variable in soil fertility and agricultural production systems.

3. Definition of Soil pH

Soil pH refers to the concentration of hydrogen ions (H^+) in the soil solution and is a fundamental indicator of soil acidity or alkalinity. It is commonly measured on a logarithmic scale ranging from 0 to 14, where:

- **pH < 7:** Acidic soil, indicating a higher concentration of hydrogen ions.
- **pH = 7:** Neutral soil, representing an equal balance of hydrogen and hydroxide ions.
- **pH > 7:** Alkaline (basic) soil, where the concentration of hydroxide ions exceeds that of hydrogen ions.

The pH level of soil is crucial because it governs the solubility and chemical forms of many essential nutrients and minerals, thereby directly influencing their availability to plants. A slightly acidic to neutral pH range (approximately 6.0–7.0) is generally considered optimal for most crops, as it ensures maximum availability of macro- and micronutrients. However, different plant species exhibit distinct pH preferences, which makes soil pH management a critical component of diversified and sustainable agricultural systems [12, 14]. Owing to its central control over nutrient dynamics, microbial activity, and root growth, soil pH is rightly regarded as a master variable in soil fertility and crop productivity.

4. Factors Affecting Soil pH

Soil pH is influenced by a combination of natural processes and human interventions. Understanding these factors is essential for effective soil management in agricultural and horticultural systems.

4.1 Parent Material

The mineral composition of the parent material plays a major role in determining inherent soil pH. Soils derived from limestone or basalt are generally alkaline, whereas those formed from

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granite or sandstone are often acidic [7, 11]. The presence of specific minerals such as iron, aluminium, and calcium further influences soil reaction. Soils rich in calcium carbonate (lime) typically exhibit higher pH values, while soils with high organic matter content often tend toward lower pH due to organic acid formation during decomposition [8, 10].

4.2 Climate

Climate, particularly rainfall and temperature, strongly affects soil pH. In regions with high rainfall, basic cations such as calcium and magnesium are leached from the soil profile, resulting in progressive acidification. Additionally, rainfall may contribute acidic compounds derived from atmospheric sources, further lowering soil pH [9, 16]. Temperature also influences microbial activity and organic matter decomposition. In tropical climates, where decomposition rates are high, soils often become more acidic due to rapid production of organic and inorganic acids [18, 19].

4.3 Human Activities

Human interventions significantly modify soil pH, especially under intensive agricultural systems.

- **Fertilizers and amendments:** The long-term use of nitrogenous fertilizers, particularly ammonium-based fertilizers, promotes soil acidification through nitrification processes. In contrast, the application of lime is a common practice to raise soil pH and ameliorate soil acidity [12, 17].
- **Irrigation:** Excessive irrigation, especially with saline or sodic water, can increase soil pH and induce alkalinity, whereas poor drainage conditions may enhance acidification processes [20, 25].
- **Agricultural practices:** Continuous monocropping, intensive tillage, and flooding practices can alter soil pH. For example, rice paddies maintained under submerged conditions often develop more acidic environments due to anaerobic decomposition of organic matter and associated biochemical reactions [21, 13].

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4.4 Biological Activity

Soil organisms, including bacteria, fungi, and earthworms, play an important role in regulating soil pH. The decomposition of organic matter by microorganisms releases organic acids, which can lower soil pH over time [22, 24]. In addition, nitrogen-fixing bacteria associated with legumes can influence soil pH through the production and transformation of nitrogenous compounds, contributing to soil acidification under certain conditions [23, 26]. Thus, biological processes act both as drivers and regulators of soil pH dynamics.

5. Soil pH and Its Relationship with Soil Chemistry

Soil pH is closely linked to soil chemical reactions, particularly those governing nutrient solubility, ion exchange, and microbial-mediated transformations. The pH level controls the dissociation of chemical compounds in the soil solution and, consequently, the availability of essential nutrients to plants [35, 37].

5.1 Nutrient Availability

- **Acidic soils (pH < 6):** In acidic conditions, elements such as iron, manganese, and aluminium become more soluble and may reach toxic concentrations for plants if excessively accumulated [28, 34]. At the same time, the availability of essential base cations such as calcium, magnesium, and potassium is reduced, which can limit plant growth.
- **Alkaline soils (pH > 7):** Under alkaline conditions, nutrients such as iron, zinc, and phosphorus become less soluble and less available to plants, often resulting in widespread micronutrient deficiencies, particularly in soils with pH above 8.0 [29, 33].
- **Neutral soils (pH 6–7):** This range is generally considered optimal for most crops, as it (ensures) balanced availability of major nutrients such as nitrogen, phosphorus, and potassium, along with trace elements like copper, zinc, and manganese [30, 32].

These relationships clearly demonstrate why soil pH is a key regulator of soil fertility and crop productivity.

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5.2 Soil Microbial Activity

Soil microorganisms, including bacteria, fungi, and earthworms, play crucial roles in nutrient cycling, organic matter decomposition, and soil structure formation. These organisms are highly sensitive to soil pH, and each group exhibits specific pH optima for growth and activity [31, 36]. For instance, nitrogen-fixing bacteria generally perform best in neutral to slightly acidic soils, whereas many decomposer fungi prefer mildly acidic conditions [37, 38]. Consequently, changes in soil pH can alter microbial community structure and function, leading to cascading effects on nutrient availability, soil health, and plant growth [38, 39].

5.3 Soil Buffering Capacity

Soil buffering capacity refers to the ability of soil to resist changes in pH when acidic or alkaline substances are added. Soils rich in clay and organic matter typically exhibit high buffering capacity due to their greater cation exchange capacity and reactive surfaces, allowing them to maintain relatively stable pH over time [40, 43]. In contrast, sandy soils with low organic matter content have low buffering capacity and are more prone to rapid pH fluctuations in response to fertilizers, irrigation water, or atmospheric deposition [42, 44]. Buffering capacity, therefore, plays a critical role in determining the stability of soil pH and the effectiveness of soil pH management strategies.

6. Soil pH and Its Influence on Plant Growth

Soil pH plays a crucial role in determining plant health and productivity by regulating nutrient availability, microbial activity, and the overall soil chemical environment. An optimal soil pH ensures efficient nutrient uptake, supports beneficial microbial communities, and promotes healthy root development. Consequently, understanding the influence of soil pH on plant growth is essential for effective soil management and sustainable agricultural production [41, 45]. This section discusses the effects of soil pH on nutrient uptake, microbial dynamics, root function, and overall plant performance [46, 48].

6.1 Nutrient Availability and Uptake

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Soil pH strongly influences the solubility and chemical form of nutrients in soil, thereby determining their availability to plants. Each nutrient responds differently to changes in pH, and these interactions directly affect plant growth and yield [47, 49].

6.1.1 Acidic Soils (pH < 6.0)

In acidic conditions, elements such as aluminium, manganese, and iron become more soluble. Although some of these elements are essential micronutrients, their excessive solubility may lead to toxicity, particularly aluminium and manganese, which can damage root systems and restrict plant growth [50, 52]. At the same time, the availability of essential nutrients such as calcium, magnesium, and phosphorus decreases due to increased fixation and reduced solubility, often resulting in nutrient deficiencies and poor crop performance [51, 54].

6.1.2 Alkaline Soils (pH > 7.0)

In alkaline soils, the solubility of several micronutrients, including iron, zinc, copper, and manganese, is markedly reduced, leading to frequent deficiency symptoms in crops [53, 59]. Phosphorus availability is also adversely affected under alkaline conditions, as it tends to form insoluble compounds with calcium and magnesium, thereby limiting its uptake by plants and negatively influencing root development and energy metabolism [54, 58].

6.1.3 Neutral Soils (pH 6.0–7.0)

Neutral to slightly acidic soils generally provide the most favourable conditions for plant growth, as the majority of essential nutrients—including nitrogen, phosphorus, potassium, calcium, magnesium, and micronutrients—are present in forms that are readily available for plant uptake. This explains why most agricultural crops perform best within this pH range [55, 57].

6.2 Impact of Soil pH on Microbial Activity

Soil microorganisms play a vital role in nutrient cycling, organic matter decomposition, and the maintenance of soil structure. These organisms are highly sensitive to soil pH, and even small changes in pH can significantly alter microbial community structure and function [56, 61].

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6.2.1 Microbial Diversity and Function

Soil pH regulates both the diversity and activity of microbial populations. Nitrogen-fixing bacteria generally perform best in neutral to slightly acidic soils, whereas many decomposer fungi prefer mildly acidic conditions [59, 60]. In strongly acidic soils, microbial diversity may decline, and the activity of beneficial organisms involved in nutrient cycling may be suppressed [57, 62]. Similarly, in alkaline soils, the activity of many beneficial microbes is constrained due to nutrient limitations and unfavorable chemical conditions, which can reduce nutrient cycling efficiency and overall soil health [63–69].

6.2.2 Soil-Borne Diseases

Soil pH also influences the incidence and severity of soil-borne diseases. Certain pathogens thrive under specific pH conditions, whereas others are inhibited. For example, some Fusarium species are more prevalent in slightly alkaline soils. Maintaining soil pH within an optimal range can therefore help suppress pathogenic organisms and reduce disease pressure in crops [64, 67].

6.3 Root Function and Soil pH

Root growth and function are strongly influenced by soil pH, as pH affects both soil chemical properties and the rhizosphere environment.

6.3.1 Root Growth and Development

In strongly acidic soils, increased solubility of toxic elements such as aluminium can damage root cells, inhibit root elongation, and reduce the plant's capacity to absorb water and nutrients [67, 68]. In alkaline soils, nutrient imbalances and micronutrient deficiencies can impair root function and limit water uptake [57, 61]. In contrast, neutral soils generally provide the most favourable conditions for root growth due to balanced nutrient availability and minimal toxic element interference [65, 72].

6.3.2 Water and Nutrient Uptake

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Soil pH influences the efficiency of water and nutrient absorption by plant roots. Under highly acidic or alkaline conditions, nutrient imbalances and root damage may restrict uptake processes, whereas in neutral soils, both water and nutrients are absorbed more efficiently, supporting vigorous plant growth and higher productivity [70, 73].

6.4 Soil pH and Overall Plant Health

Beyond nutrient availability and microbial activity, soil pH also affects plant tolerance to environmental stresses and resistance to diseases [42, 49]. In strongly acidic soils, plants often suffer from nutrient deficiencies, metal toxicity, and poor root development, which may manifest as chlorosis, stunted growth, and reduced biomass accumulation [47, 49]. Similarly, in alkaline soils, limited availability of micronutrients such as iron and zinc frequently results in chlorosis, poor growth, and reduced yield [71, 74]. In contrast, soils with near-neutral pH generally provide a stable and balanced environment that supports optimal plant health and productivity [66, 67]. Furthermore, plants grown under optimal pH conditions tend to exhibit greater resistance to diseases, whereas pH-induced nutrient stress can weaken plant defence mechanisms and increase susceptibility to pathogens [5, 47, 75].

7. Optimal Soil pH for Different Crops

Different crops exhibit distinct pH preferences that influence their growth, nutrient uptake, and yield potential. Although most crops perform best in slightly acidic to neutral soils (pH 6.0–7.0), some species are adapted to more acidic or more alkaline conditions. Understanding these requirements is essential for optimizing soil management and crop productivity [47, 49].

8. Managing Soil pH for Optimum Plant Growth

Proper soil pH management is essential for sustaining crop productivity and preventing nutrient imbalances or toxicities. This involves regular soil testing, appropriate amendment strategies, and long-term monitoring [47, 52].

9. Effects of Soil pH on Soil Microbial Populations

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Soil pH is a dominant factor controlling microbial diversity, activity, and nutrient cycling processes. Neutral to slightly acidic soils generally support the most diverse and active microbial communities, promoting efficient nitrogen fixation, phosphorus solubilization, and organic matter decomposition [7, 19, 47, 56]. In contrast, strongly acidic or highly alkaline soils often exhibit reduced microbial diversity, impaired decomposition rates, and disrupted nutrient cycling, ultimately leading to lower soil fertility and reduced crop performance [27, 39, 59].

10. Challenges and Risks in Soil pH Management

Improper pH management can result in over-liming or over-acidification, nutrient imbalances, delayed crop responses, and adverse environmental impacts. Excessive liming may induce micronutrient deficiencies, whereas excessive acidification can cause metal toxicity and microbial suppression [47, 54, 69]. Moreover, pH amendments often act slowly, creating management challenges under intensive cropping systems [27, 39, 75]. Environmentally, excessive use of amendments may contribute to nutrient leaching, runoff, and increased carbon footprint, highlighting the need for careful, soil-test-based pH management strategies [34, 36, 47, 59].

9. Future Directions in Soil pH Research

Future research is increasingly focused on precision soil pH management, advanced sensing technologies, and understanding the interactions between soil pH and climate change. Real-time pH sensors, integration with precision agriculture tools, and site-specific amendment strategies are expected to improve efficiency and sustainability of soil pH management [45, 52, 56, 67]. Additionally, long-term studies on soil health, carbon sequestration, and the role of organic matter in buffering pH fluctuations will be crucial for developing resilient and climate-smart agricultural systems [34, 36, 64, 66].

10. Management of Soil pH

10.1. Liming

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Application of lime materials (e.g., calcium carbonate) to acidic soils raises pH and improves nutrient availability and crop yields. Meta-analyses have shown that liming increases soil pH and yields in a range of cropping systems.

10.2. Acidification and Organic Amendments

For alkaline soils, acidifying fertilizers and organic amendments can help moderate pH over time. Organic amendments also enhance soil structure and microbial health, improving nutrient cycling.

10.3. Precision Management

Site-specific soil testing and variable rate amendment application allow efficient management of pH spatial variability within fields, optimizing nutrient availability and crop performance across landscapes.

11. Challenges and Future Directions

Although the optimal pH range for most crops lies between 6.0 and 7.0, soils often fall outside this range due to parent material, climate, and management practices. Future research should aim to:

- Develop better pH monitoring tools,
- Breed crop varieties tolerant of pH extremes,
- Integrate precision amendment strategies with climate-smart agriculture.

The role of soil pH under changing climatic conditions and its interaction with nutrient dynamics remains a key research frontier.

12. Conclusion

Soil pH is a foundational determinant of soil fertility and crop productivity because it regulates nutrient availability, microbial processes, and plant physiological responses. As a true "master variable," soil pH integrates chemical, biological, and physical aspects of soil functioning and

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thereby shapes the overall performance of agroecosystems. The evidence reviewed clearly shows that strongly acidic soils are constrained by metal toxicity, reduced base cation availability, and suppressed biological activity, while highly alkaline soils are limited by micronutrient deficiencies and phosphorus fixation. In contrast, neutral to slightly acidic soils provide the most favourable conditions for balanced nutrient supply, active microbial communities, healthy root development, and stable crop yields. Effective soil pH management—through regular soil testing, judicious use of lime or acidifying amendments, incorporation of organic materials, and site-specific precision practices—remains essential for sustaining soil health and improving nutrient use efficiency. However, pH correction must be approached cautiously to avoid over-liming or excessive acidification, which can create new nutrient imbalances and environmental risks. Looking ahead, future research should focus on precision pH management, long-term soil health monitoring, and the interactions between soil pH, climate change, and cropping systems. By maintaining soil pH within an optimal range, farmers and land managers can enhance soil resilience, improve crop productivity, and support the long-term sustainability of agricultural systems.

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Saline Soils: Distribution, Impact on Crop Production, and Management Strategies – A Review

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Abstract

Soil salinity is one of the most severe forms of land degradation limiting agricultural productivity, particularly in arid and semi-arid regions where irrigation is essential for crop production. The accumulation of soluble salts in the root zone adversely affects soil physical, chemical, and biological properties, resulting in poor soil structure, nutrient imbalance, reduced microbial activity, and ultimately significant yield losses in many important crops. According to the Food and Agriculture Organization, soil salinization is an expanding global challenge that poses a serious threat to food security, especially in irrigated agricultural systems. This review presents a comprehensive overview of the definition and classification of saline soils, their origin and distribution, and their effects on soil properties and crop growth. It also discusses methods for assessment and mapping of saline soils, and critically examines integrated management and reclamation strategies, including physical, chemical, biological, and agronomic approaches. Special emphasis is given to sustainable and site-specific practices such as drainage and leaching, chemical amendments, organic matter management, use of salt-tolerant crops, and improved irrigation strategies. The role of research, policy support, and future technological interventions is also highlighted. Overall, the review underscores that effective management of saline soils requires a holistic and coordinated approach to restore soil health, enhance crop productivity, and ensure long-term agricultural sustainability under changing climatic conditions.

Keywords: Saline soils, salt stress, soil degradation, crop productivity, reclamation, sustainable agriculture

1. Introduction

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Soil salinity is widely recognized as one of the most serious constraints to agricultural production across the world, particularly in arid and semi-arid regions where evapotranspiration exceeds precipitation and irrigation is essential for crop cultivation. The accumulation of soluble salts in the root zone adversely affects soil health and crop performance by creating unfavorable physical, chemical, and biological conditions for plant growth. A substantial proportion of the world's irrigated agricultural lands are affected by salinity to varying degrees, resulting in significant yield reductions in many economically important crops such as rice, wheat, cotton, and vegetables. The problem is not only agronomic but also socio-economic, as salinity directly threatens farmers' livelihoods and regional food security.

According to the Food and Agriculture Organization, soil salinization is an expanding global challenge and represents a growing threat to food security, particularly in regions where irrigation is indispensable for sustaining crop production. In many irrigated command areas, continuous use of water without adequate drainage, coupled with high evaporation rates, leads to the gradual buildup of salts in the soil profile. Over time, this process reduces soil productivity, limits crop choice, and increases the cost and complexity of land management and reclamation. In countries like India, the problem of soil salinity and sodicity affects millions of hectares of agricultural land, especially in canal-irrigated tracts, arid and semi-arid regions, and coastal zones. These areas are particularly vulnerable due to shallow and saline groundwater tables, seawater intrusion in coastal belts, and the long-term use of marginal-quality irrigation water. The situation is further aggravated by climate change, which is expected to intensify salinity risks through rising temperatures, altered rainfall patterns, increased evapotranspiration, and more frequent extreme weather events such as droughts and storm surges. Such changes can accelerate salt accumulation in soils and expand the extent of salt-affected lands. Given the scale and complexity of the problem, a clear understanding of the nature, origin, and behavior of saline soils is essential for developing effective and sustainable management strategies. Integrated approaches that combine sound soil, water, and crop management practices are required to mitigate the adverse effects of salinity and to restore the productivity of salt-affected lands. Therefore, addressing soil salinity is not only a technical necessity but also a critical component of achieving long-term agricultural sustainability and food security in vulnerable regions.2.

Definition and Classification of Saline Soils

Saline soils are soils that contain excessive amounts of soluble salts in the root zone, primarily chlorides, sulfates, and bicarbonates of sodium, calcium, and magnesium. These soils are generally characterized by:

- Electrical conductivity (ECe) of the saturated soil extract > 4 dS m^{-1}
- pH usually < 8.5
- Exchangeable sodium percentage (ESP) < 15

Based on salt composition and soil reaction, salt-affected soils are broadly classified into:

1. Saline soils
2. Sodic (alkali) soils
3. Saline-sodic soils

This classification is important because each category requires different management and reclamation strategies.

3. Origin and Distribution of Saline Soils

Saline soils may be primary (natural) or secondary (human-induced) in origin.

3.1 Natural Causes

- Weathering of parent rocks rich in soluble salts
- Deposition of salts through marine transgressions or aeolian processes
- Capillary rise of saline groundwater in arid and semi-arid climates

3.2 Human-Induced Causes

- Excessive and inefficient irrigation without adequate drainage
- Use of saline or sodic irrigation water

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- Seepage from canals and reservoirs
- Deforestation and land-use changes affecting the water balance

Globally, large tracts of saline soils are found in Central and West Asia, Australia, parts of Africa, and South Asia. In India, major salt-affected areas occur in Rajasthan, Gujarat, Haryana, Punjab, Uttar Pradesh, and coastal regions.

4. Effects of Salinity on Soil Properties

Soil salinity exerts profound influences on the physical, chemical, and biological properties of soils, thereby degrading overall soil quality and limiting its capacity to support healthy crop growth. According to the Food and Agriculture Organization, salt accumulation in soils not only affects plant performance directly but also alters fundamental soil processes that govern water movement, nutrient availability, and biological activity. These changes are often interrelated and tend to reinforce one another, leading to a progressive decline in soil productivity if not properly managed.

4.1 Physical Properties

Salinity, particularly when associated with high levels of exchangeable sodium, has a detrimental effect on soil physical condition. One of the most common problems observed in saline and sodic soils is poor soil structure and surface crusting. In sodic and saline-sodic soils, excess sodium causes dispersion of soil clay particles, which destroys stable soil aggregates. As a result, the soil surface becomes dense and compacted, forming crusts that hinder seedling emergence and reduce gaseous exchange between the soil and the atmosphere. Another major consequence is reduced infiltration and permeability. Dispersed clay particles clog soil pores, especially the larger pores responsible for rapid water movement. This leads to slow water infiltration, poor internal drainage, and increased surface runoff. Under such conditions, irrigation water tends to stagnate on the surface, increasing the risk of water logging and further salt accumulation in the root zone. Saline and sodic soils also commonly exhibit increased bulk density and compaction problems. The breakdown of soil aggregates and collapse of pore spaces result in a denser soil mass with fewer macro pores. High bulk density restricts root penetration, reduces aeration, and limits the movement of water and nutrients within the soil profile. Together, these physical constraints create an

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unfavorable root environment and significantly reduce the soil's capacity to support healthy crop growth.

4.2 Chemical Properties

From a chemical perspective, the most immediate effect of salinity is the high concentration of soluble salts in the soil solution, which increases the osmotic potential. This makes it more difficult for plant roots to absorb water, even when the soil appears to be adequately moist, leading to a condition often described as "physiological drought." As salinity increases, plants must expend more energy to take up water, which reduces growth and productivity. Salinity also causes nutrient imbalance and reduced availability of essential plant nutrients such as nitrogen, phosphorus, potassium, calcium, and several micronutrients. High concentrations of sodium and chloride ions can interfere with the uptake of potassium and calcium due to ionic competition at root surfaces. In addition, high soil salinity can reduce the solubility or mobility of certain nutrients, leading to deficiencies even when total nutrient content in the soil is adequate. Another important chemical constraint is the potential toxicity of specific ions, particularly sodium (Na^+), chloride (Cl^-), and boron (B^{3+}). When these ions accumulate in excessive amounts in the soil and plant tissues, they can disrupt metabolic processes, damage cellular structures, and impair enzyme activity. Ion toxicity often manifests as leaf burn, chlorosis, premature leaf drop, and overall decline in plant vigor, especially in salt-sensitive crops.

4.3 Biological Properties

Soil salinity also has a strong negative impact on the biological health of soils. High salt concentrations create an unfavorable environment for many soil microorganisms, leading to reduced microbial activity and biomass. Since soil microbes play a crucial role in nutrient cycling, organic matter decomposition, and the formation of stable soil aggregates, their decline further कमजोरens soil fertility and structure. The rate of organic matter decomposition is generally slower in saline soils because microbial populations responsible for breaking down organic residues are suppressed by osmotic stress and ion toxicity. This results in slower nutrient release and reduced availability of nitrogen, phosphorus, and sulfur to plants, further compounding fertility problems.

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5. Effects of Salinity on Crop Growth and Yield

Salinity affects plants through three major mechanisms:

1. Osmotic stress: High salt concentration in soil solution makes water uptake difficult for roots, leading to physiological drought.
2. Ion toxicity: Excess accumulation of Na^+ and Cl^- in plant tissues damages cellular structures and metabolic processes.
3. Nutrient imbalance: High salt levels interfere with the uptake of essential nutrients such as K^+, Ca^{2+}, and NO_3^-.

Visible symptoms of salt stress include poor germination, stunted growth, leaf chlorosis, leaf burn, premature senescence, and reduced yield. Crops vary widely in their salt tolerance; for example, barley and cotton are relatively tolerant, whereas rice, beans, and most vegetables are sensitive.

6. Assessment and Mapping of Saline Soils

Saline soils are commonly assessed using:

- Electrical conductivity (ECe) of soil extract
- Soil pH and exchangeable sodium percentage (ESP)
- Sodium adsorption ratio (SAR) of soil or irrigation water

Modern approaches include remote sensing and GIS techniques for large-scale mapping and monitoring of salt-affected areas, which help in planning reclamation and management strategies more effectively.

7. Management and Reclamation of Saline Soils

Effective management and reclamation of saline soils require an integrated and site-specific approach that combines physical, chemical, biological, and agronomic measures. The objective is not only to remove or reduce excess salts from the root zone, but also to restore and maintain favorable soil physical conditions, improve nutrient availability, and ensure sustainable crop productivity. International agencies such as the Food and Agriculture Organization emphasize that long-term success in managing salt-affected soils depends on

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the coordinated management of soil, water, and crops rather than reliance on a single technique. Similarly, in India, research and extension efforts led by institutions like the Indian Council of Agricultural Research have demonstrated that integrated reclamation strategies are more effective and economically viable than isolated interventions.

7.1 Physical Methods

Physical methods form the foundation of saline soil management, as they directly address the movement and removal of excess salts from the soil profile. The most important requirement is the provision of adequate surface and subsurface drainage, which prevents the rise of saline groundwater and facilitates the downward movement of salts beyond the root zone. Without proper drainage, any attempt at leaching or amendment application becomes ineffective, as salts tend to re-accumulate in the upper soil layers. Leaching of soluble salts using good-quality irrigation water is another key practice. This involves applying sufficient water to dissolve and transport salts below the active root zone, thereby reducing salinity stress on crops. The efficiency of leaching depends on soil texture, structure, permeability, and the quality of irrigation water. Coarse-textured soils generally respond more quickly to leaching, whereas fine-textured and poorly structured soils require careful water management to avoid waterlogging and secondary salinization. Land leveling and proper irrigation scheduling also play a crucial role in preventing salt accumulation. Uneven fields lead to non-uniform water distribution, causing salts to accumulate in poorly irrigated or elevated patches. Proper leveling ensures uniform infiltration and leaching, while scientifically planned irrigation scheduling helps maintain an optimal soil moisture regime and minimizes the upward movement of salts through capillary rise, especially in arid and semi-arid environments.

7.2 Chemical Methods

Chemical methods are particularly important in the reclamation of sodic and saline-sodic soils, where excess exchangeable sodium adversely affects soil structure, permeability, and aeration. The most widely used chemical amendment is gypsum (calcium sulfate), which supplies soluble calcium to the soil. Calcium replaces sodium on the soil exchange complex, and the displaced sodium is subsequently leached out of the root zone with irrigation or rainwater. This process improves soil aggregation, increases infiltration rate, and enhances overall soil physical condition. In calcareous sodic soils, where native calcium carbonate is

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present but poorly soluble, sulfur or acid-forming materials (such as elemental sulfur or pyrite) may be applied. These materials generate acidity in the soil, which helps dissolve calcium carbonate and release calcium into the soil solution, thereby facilitating the replacement of exchangeable sodium. The effectiveness of such amendments depends on soil properties, microbial activity, and proper moisture management. For best results, the combined use of chemical amendments and leaching is essential. While amendments correct the chemical imbalance of the soil, leaching ensures the physical removal of soluble salts and displaced sodium from the root zone. Without adequate leaching, the benefits of chemical amendments remain limited and temporary.

7.3 Biological and Organic Approaches

Biological and organic approaches play a supportive yet critical role in improving the long-term health and resilience of saline soils. The incorporation of organic manures, compost, and green manures helps improve soil structure, enhances aggregate stability, increases water-holding capacity, and stimulates microbial activity. These improvements facilitate better root growth, increase infiltration, and indirectly promote the leaching of salts. The use of salt-tolerant grasses and halophytes is often recommended during the initial stages of reclamation, particularly in severely salt-affected areas. Such plants can survive and grow under high salinity conditions, provide ground cover, reduce surface evaporation, and contribute organic matter to the soil. Over time, this biological intervention helps stabilize the soil surface, improve soil structure, and create more favorable conditions for the introduction of moderately salt-tolerant crops. Crop residue management is another important practice, as retaining and incorporating residues enhances soil organic carbon content and buffering capacity against salinity stress. Increased organic matter improves cation exchange capacity, nutrient availability, and microbial activity, all of which contribute to better soil functioning under saline conditions.

7.4 Agronomic Practices

Agronomic management is crucial for ensuring crop productivity in saline environments and for making reclamation efforts economically sustainable. The selection of salt-tolerant crop varieties and suitable cropping systems is one of the most practical and cost-effective strategies. Different crops and even varieties within the same crop differ widely in their

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tolerance to salinity, and choosing appropriate genotypes can significantly reduce yield losses. Proper seedbed preparation and planting methods, such as the ridge and furrow system, help minimize salt injury during germination and early seedling growth, which are the most sensitive stages of crop development. Planting on ridges, for example, keeps the root zone relatively less saline compared to furrows where salts tend to accumulate due to evaporation. Balanced fertilization and micronutrient management are also essential, as salinity often leads to nutrient imbalances and reduced availability of essential elements such as nitrogen, phosphorus, potassium, zinc, and iron. Adequate and balanced nutrient supply helps crops better withstand salinity stress and improves overall growth and yield. Finally, the conjunctive use of saline and non-saline water for irrigation is an important water management strategy in areas with limited freshwater resources. By alternating or blending waters of different qualities and applying them at appropriate growth stages, it is possible to reduce salt stress on crops while conserving good-quality water and maintaining acceptable soil salinity levels.

8. Role of Research and Policy Support

In countries like India, institutions such as the Indian Council of Agricultural Research have played a significant role in developing salt-tolerant varieties, reclamation technologies, and management practices for salt-affected soils. However, large-scale adoption requires strong policy support, farmer awareness programs, and investment in drainage and irrigation infrastructure.

9. Future Perspectives

With increasing pressure on land and water resources and the impacts of climate change, the problem of soil salinity is expected to intensify in many regions. Future research should focus on:

- Breeding and biotechnology approaches for developing highly salt-tolerant crops
- Precision irrigation and soil management techniques
- Use of remote sensing and decision-support systems for early detection and management
- Promotion of climate-resilient and resource-efficient farming systems

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10. Conclusion

Soil salinity represents a major and growing challenge to sustainable agriculture, particularly in irrigated, arid, semi-arid, and coastal regions. The accumulation of soluble salts in the soil profile leads to profound deterioration of soil physical, chemical, and biological properties, which in turn restricts root growth, disrupts nutrient uptake, reduces microbial activity, and ultimately results in substantial losses in crop yield and land productivity. The adverse effects of salinity are further intensified by improper irrigation practices, inadequate drainage, use of poor-quality water, and the emerging impacts of climate change. This review highlights that saline soils originate from both natural and human-induced processes and are widely distributed across many parts of the world, including large areas of India. The impacts of salinity on soil properties and crop performance are complex and interrelated, involving osmotic stress, ion toxicity, and nutrient imbalances. Therefore, no single practice can effectively address the problem. Instead, successful management and reclamation of saline soils depend on an integrated, site-specific approach that combines physical measures such as drainage and leaching, chemical amendments like gypsum and acid-forming materials, biological and organic interventions to improve soil health, and sound agronomic practices including the use of salt-tolerant crops and efficient water and nutrient management. In India, the efforts of institutions such as the Indian Council of Agricultural Research have been instrumental in developing salt-tolerant varieties and improved reclamation technologies. However, wider adoption of these technologies requires strong policy support, investment in irrigation and drainage infrastructure, and effective extension and farmer awareness programs. Looking ahead, future strategies should focus on breeding and biotechnology for enhanced salt tolerance, precision soil and water management, and the use of remote sensing and decision-support tools for early detection and monitoring of salinity. Addressing soil salinity in a comprehensive and sustainable manner is not only essential for restoring degraded lands but also for safeguarding long-term food security and agricultural resilience in the face of increasing environmental and climatic pressures.

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Integrated Resource Management for Sustainable Wheat (*Triticum aestivum* L.) Production in the South-Eastern Region of Rajasthan

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Abstract

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops in India and plays a major role in ensuring food security, nutritional stability, and economic development. It is widely cultivated across different agro-climatic regions of the country and serves as a staple food for millions of people. Due to increasing population pressure and limited cultivable land, there is a growing need to enhance wheat productivity through sustainable agricultural practices. Among the various factors affecting wheat production, irrigation and nutrient management are considered the most important. Proper irrigation at critical growth stages and balanced nutrient supply are essential for achieving higher grain yield and maintaining soil fertility. Excessive use of chemical fertilizers alone may provide immediate crop response, but continuous application over a long period can negatively affect soil health, reduce microbial activity, and lower nutrient use efficiency. Therefore, integrated nutrient management, which combines chemical fertilizers with organic sources such as farmyard manure (FYM), has emerged as an effective approach for sustainable crop production. FYM improves soil structure, increases water-holding capacity, enhances soil organic carbon, and promotes better nutrient availability. Keeping these aspects in view, the present study was conducted during the Rabi season of 2025–26 at the Agricultural Instructional Farm, School of Agricultural Sciences, Career Point University, Kota, Rajasthan. The experiment was designed to evaluate the effect of different irrigation schedules and fertility source treatments on wheat growth, yield, quality, soil fertility, and economic returns. The soil of the experimental field was silty loam in texture, slightly alkaline in reaction, low in organic carbon, and medium in fertility status. The experiment consisted of four irrigation levels and four fertility source treatments arranged in a split plot design with three replications. The irrigation treatments included one irrigation at Crown Root Initiation (CRI) stage, two irrigations at CRI and flowering stages, three irrigations at CRI, late jointing, and milk stages, and four irrigations at CRI, tillering, flowering, and milk stages. Fertility treatments included 100 percent recommended dose of fertilizers (RDF) through chemical fertilizers, 75 percent RDF through fertilizers + 25 percent FYM, 50 percent RDF through fertilizers + 50 percent FYM, and 100 percent RDF through FYM. The results of the study revealed that higher irrigation frequency significantly improved plant height, number of tillers, dry matter accumulation, leaf area index, grain yield, straw yield, and water use efficiency. Among the irrigation treatments, four irrigations at CRI, tillering, flowering, and milk stages produced the highest growth and yield. Similarly, integrated nutrient management treatments performed better than sole application of fertilizers or FYM. The treatment receiving 75 percent RDF through fertilizers combined with 25 percent FYM recorded the highest grain yield, better nutrient uptake, improved grain quality, and maximum economic returns. Therefore, the study concluded that integrated irrigation and nutrient management is essential for sustainable wheat production and long-term soil health.

Keywords: Wheat, Irrigation Scheduling, Integrated Nutrient Management, Farmyard Manure

1. Introduction

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops in the world and serves as a staple food for a large proportion of the global population. In India, wheat occupies a prominent place in the agricultural sector and is the second most important food crop after rice. It contributes significantly to national food security, nutritional requirements, rural employment, and the overall economy. Wheat grains are rich in carbohydrates, proteins, vitamins, and minerals, making them an essential component of the daily diet of millions of people. India is one of the leading producers of wheat in the world, with major cultivation areas located in states such as Punjab, Haryana, Uttar Pradesh, Rajasthan, Madhya Pradesh, and Bihar. However, the continuous rise in population has increased the demand for wheat production. Since the availability of cultivable land is limited, enhancing productivity per unit area has become a major challenge for researchers and farmers. Sustainable intensification of wheat production is therefore essential to meet future food demands without degrading natural resources. Among the various factors affecting wheat productivity, irrigation and

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nutrient management play a vital role. Wheat is highly responsive to irrigation, especially at critical growth stages such as crown root initiation, tillering, flowering, and grain filling. Inadequate water supply during these stages can lead to poor growth, reduced tiller formation, lower grain filling, and ultimately decreased yield. On the other hand, excessive irrigation may result in nutrient losses, waterlogging, and inefficient use of water resources. Therefore, proper irrigation scheduling is necessary to achieve maximum productivity and water use efficiency. Similarly, balanced nutrient management is crucial for obtaining higher wheat yields and maintaining soil fertility. Traditionally, farmers rely heavily on chemical fertilizers to increase crop production. Although the use of inorganic fertilizers provides quick nutrient availability and immediate crop response, continuous and imbalanced application may adversely affect soil structure, microbial activity, and long-term soil health. Overdependence on chemical fertilizers can also lead to nutrient imbalance, soil degradation, and declining productivity over time. Integrated nutrient management, which involves the combined use of organic and inorganic nutrient sources, has emerged as an effective strategy for sustainable wheat cultivation. Farmyard manure (FYM) is an important organic source that improves soil physical, chemical, and biological properties. It enhances soil organic matter content, improves water-holding capacity, promotes microbial activity, and increases nutrient availability. When FYM is used along with recommended doses of chemical fertilizers, it not only supplies essential nutrients but also improves nutrient use efficiency and crop performance. Thus, integrated management of irrigation and nutrients is essential for achieving higher wheat productivity, better grain quality, improved soil health, and enhanced profitability. Adoption of such sustainable practices can help farmers maintain long-term productivity while conserving soil and water resources.

2. Materials and Methods

The present investigation was carried out during the Rabi season of 2025–26 at the Agricultural Instructional Farm, School of Agricultural Sciences, Career Point University, Kota, Rajasthan. The experimental site is located in the south-eastern plain zone of Rajasthan, which is characterized by a semi-arid climate with hot summers and mild winters. The region receives most of its annual rainfall during the monsoon season, while the rabi season remains comparatively dry, making irrigation management highly important for successful wheat cultivation. Before the initiation of the experiment, representative soil samples were collected from the experimental field at a depth of 0–15 cm and analyzed for their physical and chemical properties. The soil of the experimental field was silty loam in texture, slightly alkaline in reaction, low in organic carbon content, and medium in available nitrogen, phosphorus, and potassium status. The field was uniform in fertility and well-drained, making it suitable for conducting the wheat experiment. The experiment was laid out in a split plot design with three replications. Irrigation levels were assigned to the main plots, while fertility source treatments were allocated to the sub-plots. This design was adopted to study the individual as well as combined effects of irrigation and nutrient management practices on the growth, yield, quality, and economics of wheat cultivation.

Four irrigation levels were included in the study. The first treatment consisted of one irrigation applied at the Crown Root Initiation (CRI) stage. The second treatment involved two irrigations, one at the CRI stage and the other at the flowering stage. The third treatment included three irrigations applied at the CRI stage, late jointing stage, and milk stage. The fourth treatment consisted of four irrigations applied at critical growth stages, namely CRI, tillering, flowering, and milk stage. These irrigation schedules were selected to assess the response of wheat to varying levels of water availability during important growth stages. Four fertility source treatments were also evaluated in the experiment. The first treatment consisted of 100 percent recommended dose of fertilizers (RDF) supplied entirely through chemical fertilizers. The second treatment included 75 percent RDF through chemical fertilizers combined with 25 percent nutrient requirement supplied through farmyard manure (FYM). The third treatment consisted of 50 percent RDF through chemical fertilizers along with 50 percent nutrient requirement supplied through FYM. The fourth treatment involved 100 percent nutrient requirement supplied entirely through FYM. The recommended dose of fertilizers for wheat was 120:60:40 kg $N:P_2O_5:K_2O$ per hectare. Nitrogen was applied through urea, phosphorus through diammonium phosphate (DAP), and potassium through muriate of potash (MOP). Farmyard manure was incorporated into the soil before sowing according to the treatment requirements. Full doses of phosphorus and potassium and half of the nitrogen dose were applied as basal application at the time of sowing, while the remaining nitrogen was top-dressed in two equal splits during crop growth. The wheat crop was sown using a suitable seed rate and recommended agronomic practices were followed throughout the crop season. Necessary intercultural operations, weed management, plant protection measures, and irrigation applications were carried out uniformly in all treatments according to the

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experimental plan. Observations on growth parameters, yield attributes, grain yield, straw yield, quality parameters, soil fertility status, water use efficiency, and economics were recorded and analyzed statistically to determine the significance of treatment effects.

3. Review of Literature

Previous studies have indicated that irrigation management and integrated nutrient management play a crucial role in improving the productivity and sustainability of wheat cultivation. Wheat is highly sensitive to moisture stress, particularly during critical growth stages such as Crown Root Initiation (CRI), tillering, flowering, and milk stage. Adequate irrigation during these stages promotes better root growth, tiller formation, nutrient absorption, grain filling, and ultimately higher grain yield. Researchers have reported that an increase in irrigation frequency significantly improves plant height, number of tillers, leaf area index, dry matter accumulation, grain yield, and water use efficiency in wheat. Timely irrigation at critical stages such as CRI, tillering, flowering, and milk stage is highly important for improving wheat productivity and tiller development. Among different irrigation schedules, four irrigations applied at CRI, tillering, flowering, and milk stage have often been found to produce the highest grain and straw yields, along with better water use efficiency. Integrated nutrient management involving the combined use of farmyard manure (FYM) and inorganic fertilizers has also been widely recognized as an effective approach for maintaining soil fertility and improving crop performance. Continuous use of chemical fertilizers alone may lead to soil degradation and decline in soil organic matter, whereas the incorporation of organic manures helps improve soil structure, microbial activity, water-holding capacity, and nutrient availability. Combined use of FYM and inorganic fertilizers improves soil organic carbon, nutrient availability, grain yield, and soil fertility in wheat-based systems. A study conducted by the Indian Council of Agricultural Research in 2019 reported that integrated nutrient management significantly increased wheat yield, nutrient uptake, and soil fertility status in alluvial soils. The study found that partial substitution of chemical fertilizers with organic sources enhanced soil organic carbon and improved the availability of nitrogen, phosphorus, and potassium. Similarly, a study published in BMC Plant Biology in 2024 highlighted that optimizing irrigation, nutrient management, and organic amendments together improved wheat productivity, nutrient use efficiency, and soil health. The authors emphasized that balanced use of water and nutrients is essential for

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achieving sustainable wheat production. Research carried out by the Indian Council of Agricultural Research in 2025 on pearl millet–wheat systems under saline irrigation conditions revealed that integrated nutrient management practices reduced the negative effects of saline water and improved crop growth, yield, and soil fertility. Another study by the Indian Council of Agricultural Research in 2021 on rice–wheat cropping systems reported that target yield-based integrated nutrient management improved crop productivity, nutrient use efficiency, and economic returns while maintaining soil fertility over the long term.

In 2023, the Indian Council of Agricultural Research developed integrated nutrient management recommendations for late-sown wheat and found that combined use of FYM and chemical fertilizers significantly improved plant growth, grain yield, and nutrient uptake compared to sole application of fertilizers. A meta-analysis conducted by the International Rice Research Institute in 2019 also concluded that integrated nutrient management in rice–wheat cropping systems contributes to sustainable production by improving soil health, crop yield, and nutrient balance in the Indian subcontinent. Furthermore, T. Fazily, S.K. Thakra, and A.K. Dhaka in 2021 reported that integrated nutrient management significantly improved growth parameters, yield attributes, grain yield, and straw yield of wheat. Their findings confirmed that combining organic and inorganic nutrient sources is more beneficial than using either source alone. Overall, previous research findings suggest that higher irrigation frequency and integrated nutrient management practices are essential for improving wheat growth, productivity, soil fertility, and profitability. Several researchers concluded that four irrigations at critical growth stages along with partial substitution of chemical fertilizers through FYM produced the best results in wheat cultivation.

4. Results and Discussion

The results of the experiment clearly indicated that irrigation scheduling and integrated nutrient management had a significant influence on the growth, yield, quality, and soil fertility status of wheat. Higher irrigation frequency resulted in better crop growth due to improved availability of soil moisture during critical growth stages. Adequate soil moisture enhanced nutrient absorption, photosynthetic activity, and dry matter production, which ultimately contributed to higher yield.

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Among the different irrigation levels, the application of four irrigations at CRI, tillering, flowering, and milk stages recorded the highest values of plant height, number of effective tillers per square meter, dry matter accumulation, and leaf area index. These critical growth stages are highly sensitive to water stress, and timely irrigation during these periods promoted better vegetative growth and reproductive development. In contrast, the lowest growth parameters were observed under the treatment receiving only one irrigation at the CRI stage due to limited moisture availability during later stages of crop growth. Yield attributes such as number of grains per ear head, ear length, test weight, grain yield, straw yield, and biological yield were also significantly affected by irrigation treatments. The highest grain and straw yields were recorded under the four-irrigation schedule, which may be attributed to better grain filling, improved translocation of photosynthates, and greater nutrient uptake. Adequate irrigation during flowering and milk stages particularly helped in reducing grain shriveling and improving grain size and weight. The fertility source treatments also showed a marked effect on crop performance. Treatments involving combined use of inorganic fertilizers and farmyard manure (FYM) performed better than the treatments receiving only chemical fertilizers or only FYM. The integration of organic and inorganic nutrient sources ensured balanced nutrient supply throughout the crop growth period and improved the physical, chemical, and biological properties of the soil. Among the fertility treatments, the application of 75 percent recommended dose of fertilizers through chemical fertilizers along with 25 percent nutrient requirement through FYM recorded the best performance in terms of plant growth, yield attributes, nutrient uptake, and grain quality. This treatment resulted in higher grain protein content, better test weight, and increased uptake of nitrogen, phosphorus, and potassium by the crop. The superior performance of this treatment may be due to the gradual release of nutrients from FYM and the immediate availability of nutrients from chemical fertilizers, which together improved nutrient use efficiency. Integrated nutrient management also had a positive effect on post-harvest soil fertility. The combined application of FYM and fertilizers increased soil organic carbon content and improved the availability of nitrogen, phosphorus, and potassium after harvest compared to sole application of fertilizers. This indicates that integrated nutrient management not only enhances crop productivity but also helps maintain long-term soil health and sustainability. Economic analysis of the treatments revealed that higher irrigation levels combined with integrated nutrient management practices produced greater net returns and benefit-cost ratio. The treatment receiving four irrigations along with 75 percent RDF through fertilizers and 25 percent FYM was found to be the most profitable due to its higher grain yield and better input-use efficiency. Thus, the study demonstrated that balanced irrigation and nutrient management practices are essential for maximizing wheat productivity, profitability, and soil fertility under semi-arid conditions.

5. Conclusion

The findings of the present study clearly demonstrated that integrated resource management plays a vital role in achieving sustainable wheat production under semi-arid conditions. Proper management of irrigation and nutrient sources significantly influenced crop growth, yield attributes, grain quality, soil fertility, and economic returns. Among the different irrigation schedules, the application of four irrigations at critical growth stages, namely CRI, tillering, flowering, and milk stage, proved to be the most effective in enhancing plant height, tiller production, dry matter accumulation, grain filling, and overall grain yield. Adequate water supply during these stages ensured better nutrient uptake and efficient utilization of available resources. Similarly, integrated nutrient management practices involving a combination of organic and inorganic nutrient sources performed better than the sole application of fertilizers or farmyard manure. The treatment consisting of 75 percent recommended dose of fertilizers through chemical fertilizers along with 25 percent nutrient requirement supplied through FYM recorded the highest grain yield, improved grain quality, greater nutrient uptake, and better economic returns. This treatment also contributed to the improvement of soil organic carbon and available nitrogen, phosphorus, and potassium content after harvest. Therefore, it can be concluded that the combined use of four irrigations at critical growth stages along with integrated nutrient management using 75 percent RDF through fertilizers and 25 percent FYM is the most suitable approach for maximizing wheat productivity, improving water use efficiency, maintaining soil health, and enhancing profitability. Adoption of these practices can help farmers achieve higher and sustainable wheat yields while conserving soil and water resources for future generations.

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Ultra-High-Performance Concrete (Uhpc): Seismic Behavior, Ductility, and The Design of Slender Structural Elements

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Abstract: "This study presents an in-depth exploration of the seismic efficacy and ductile characteristics of Ultra-High-Performance Concrete (UHPC). As a transformative advancement in cementitious technology, UHPC delivers compressive strengths surpassing 150 MPa alongside substantial tensile capacity facilitated by steel fiber integration. By examining UHPC's micromechanical behavior and its response to cyclic deformation, this research evaluates the feasibility of optimizing cross-sectional geometries in seismically active regions. Utilizing a synthesis of experimental results and constitutive frameworks, the article illustrates UHPC's capacity to produce slender, highly resilient structural components that outperform traditional reinforced concrete." Ultra-High-Performance Concrete (UHPC) is garnering significant interest within the global structural engineering community as a transformative construction material. Although its developmental roots extend back several decades, comprehensive knowledge regarding its complex behavior and specialized properties has historically remained concentrated within select research institutions. This paper provides a foundational introduction to UHPC, detailing its unique constituent ingredients and the micromechanical principles that govern its performance. Through an extensive review of existing literature, this study synthesizes the contributions of key researchers to establish a clear picture of UHPC's structural behavior. A comparative analysis is conducted between conventional concrete and UHPC, specifically evaluating differences in stress-strain relationships, cracking mechanisms, and ultimate compressive, tensile, and shear strengths. Furthermore, the paper rigorously examines the material's enhanced durability, focusing on its exceptional resistance to moisture permeability, chloride ingress, and aggressive chemical environments. By exploring its superior impact resistance and energy absorption characteristics, the study highlights the material's potential for high-demand infrastructure. Finally, the paper documents current and emerging applications in

civil engineering, concluding with an assessment of how UHPC is poised to redefine future structural design through innovative, resilient, and sustainable engineering solutions.

Keywords: Ultra-high-performance concrete (UHPC); Mechanical behavior; Strength; Durability; Structural applications.

1. Introduction

The field of civil engineering is currently witnessing a transformative era, driven by the demand for infrastructure that is not only architecturally ambitious but also capable of withstanding extreme environmental and seismic forces. For over a century, conventional reinforced concrete (RC) has served as the global standard for construction; however, its inherent limitations—specifically its brittleness, susceptibility to environmental degradation, and massive self-weight—have necessitated the search for a new generation of cementitious materials. Ultra-High-Performance Concrete (UHPC) has emerged as the definitive answer to these challenges, representing a fundamental paradigm shift in structural design.

UHPC is not merely an incremental improvement over high-strength concrete; it is a sophisticated composite material engineered at the nanostructural level. By optimizing particle packing and integrating high-strength steel fibers, UHPC achieves a compressive strength typically exceeding 150 MPa and, more importantly, exhibits significant tensile ductility. This unique ability to "give" without breaking allows for the design of structures that are far more resilient than those built with traditional materials.

While the conceptual foundations of UHPC were laid several decades ago, its application has often been confined to specialized research circles in a few technologically advanced nations. However, as global urbanization accelerates in high-seismic zones, the need for widespread adoption has become critical. In these regions, the primary engineering goal is to dissipate energy during seismic events through ductile deformation rather than brittle failure. UHPC's internal fiber-bridging mechanism provides a level of energy absorption and crack control that conventional concrete cannot match, even with heavy reinforcement.

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This paper serves as a comprehensive guide to the current state of UHPC technology. It begins by elaborating on the material's constituent ingredients—such as silica fume, quartz sand, and superplasticizers—and describes how these components interact to create a nearly impermeable matrix. We then provide a detailed review of available research literature, synthesizing the contributions of pioneers in the field to understand the material's structural behavior under cyclic loading.

Central to this study is a comparative analysis between conventional RC and UHPC. By evaluating differences in stress-strain relationships and shear capacity, this research demonstrates the potential for slender structural design. The ability to create thinner, stronger elements not only reduces the carbon footprint and material volume of a project but also allows for innovative architectural forms that were previously deemed structurally unfeasible. Finally, the paper explores the long-term durability of UHPC, focusing on its resistance to chloride ingress and chemical attack, ensuring that the structures of tomorrow are built to last for generations.

2. Material Composition and Micromechanics

The extraordinary mechanical properties and durability of Ultra-High-Performance Concrete (UHPC) are not coincidental; they are the direct result of a meticulously engineered microstructure. While conventional concrete relies on a rocky skeleton of coarse aggregates held together by a cement paste, UHPC is designed as a dense, homogeneous matrix that eliminates the structural weaknesses inherent in traditional mixes.

2.1 The Principle of Particle Packing

The core philosophy behind UHPC is the optimization of particle packing density. By excluding coarse aggregates and utilizing a graduation of fine particles—ranging from quartz sand down to Nano-scale silica fume—the material achieves a "void-free" state. This dense arrangement is facilitated by an extremely low water-to-cementitious material (w/cm) ratio, typically falling below 0.20. Achieving workability at such low water levels is made possible through the integration of advanced High-Range Water-Reducing Admixtures (HRWR), or superplasticizers, which disperse cement particles and reduce internal friction.

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2.2 Key Components and Their Roles

The synergy of UHPC's ingredients allows it to transcend the performance limits of standard concrete. The typical proportions and functions of these components are summarized in the table below:

Component	Function in UHPC	Typical Proportion
Portland Cement	Acts as the primary hydraulic binder.	25–35% (by weight)
Silica Fume	Facilitates pozzolanic reaction and provides a "filler effect" at the nano-scale.	5–10% (by weight)
Fine Quartz Sand	Serves as the fine aggregate (maximum size ~0.6mm), ensuring matrix stability.	40–50% (by weight)
Steel Fibers	Provides crucial post-cracking ductility and micro-crack control.	2–3% (by volume)
Superplasticizer	Ensures fluid workability and high-flow characteristics at low w/c ratios.	1–2% (by weight)

2.3 Elimination of the Interfacial Transition Zone (ITZ)

In conventional concrete, the weakest link is the Interfacial Transition Zone (ITZ)—the thin region of paste surrounding large aggregate particles. This zone is typically characterized by higher porosity and a tendency to develop micro-cracks under stress.

In UHPC, the absence of coarse aggregate fundamentally alters this dynamic:

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- Reduction of Heterogeneity: The matrix becomes more uniform, which significantly minimizes internal stress concentrations.
- Densification: The use of silica fume and fine quartz ensures that the ITZ is either virtually non-existent or so highly densified that it matches the strength of the surrounding paste.
- Micro-level Reinforcement: The inclusion of high-strength steel fibers acts as a secondary "micromechanics" layer, bridging any micro-fissures that attempt to form, thereby preventing them from coalescing into macro-cracks.

This transition from a heterogeneous, aggregate-dependent material to a dense, fiber-reinforced composite is what allows UHPC to sustain immense compressive loads and exhibit its signature tensile toughness.

3. Compressive and Tensile Behavior of UHPC

The mechanical superiority of UHPC is most evident in its extreme strength parameters and its departure from the brittle failure modes associated with traditional cementitious materials. By decoupling strength from bulk, UHPC allows for structural efficiencies previously reserved for steel construction.

3.1 Compressive Strength

While conventional reinforced concrete typically operates within a strength range of 20 to 50 MPa, UHPC routinely achieves compressive strengths between 150 and 200 MPa. This nearly five-fold increase in load-bearing capacity facilitates a radical optimization of structural geometry:

- Sectional Reduction: Structural members, particularly columns in high-rise buildings, can undergo a massive reduction in cross-sectional area.
- Space Optimization: Thinner columns translate directly into increased usable floor area, providing significant economic advantages for developers and architects.
- Dead Load Mitigation: By reducing the volume of material required, the overall dead load of the superstructure is significantly lowered. This reduction creates a cascading benefit,

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allowing for smaller, more cost-effective foundation systems and improved performance under seismic inertial forces.

3.2 Tensile Ductility

While its compressive strength is impressive, the truly defining feature of UHPC is its unique tensile behavior. Standard concrete is inherently brittle; it possesses negligible tensile strength and fails abruptly once the first crack forms. UHPC, however, fundamentally alters this mechanism through the integration of high-strength steel fibers.

- The Strain-Hardening Phase: Unlike traditional concrete, which enters a "softening" phase (immediate loss of strength) after cracking, UHPC exhibits a strain-hardening response. This means the material can continue to sustain increasing tensile loads even after the matrix has cracked.
- The Fiber-Bridging Mechanism: This ductility is achieved through the mechanical action of steel fibers. As micro-cracks develop, the fibers bridge the openings, effectively transferring stresses across the cracks and preventing them from widening into structural failures.
- Energy Absorption: This behavior allows the material to absorb significant energy and undergo large deformations, providing a critical safety buffer in extreme loading scenarios such as earthquakes or impacts.

4. Seismic Performance and Cyclic Loading

In the domain of earthquake engineering, the primary objective is to design structures capable of sustaining large lateral displacements without a total loss of load-carrying capacity. The transition from traditional reinforced concrete (RC) to Ultra-High-Performance Concrete (UHPC) represents a significant leap in how structures manage these extreme dynamic forces.

4.1 Internal Confinement and Shear Resistance

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Traditional RC design is heavily dependent on secondary steel reinforcement—specifically transverse stirrups and ties—to provide confinement for the concrete core. This confinement is essential to prevent brittle shear failure and to allow the longitudinal rebar to reach its plastic limit.

In contrast, UHPC transforms the concrete matrix itself into a primary structural reinforcement system:

- The Role of Steel Fibers: The dense network of steel fibers distributed throughout the UHPC matrix provides inherent "internal confinement."
- Shear Capacity: These fibers act as multi-directional micro-reinforcement, resisting diagonal tension and shear stresses. This often allows for a dramatic reduction in—or even the total elimination of—congested transverse stirrups, simplifying the construction process while enhancing safety.

4.2 Hysteretic Behavior and Energy Dissipation

The performance of a structural element during an earthquake is best evaluated through its response to cyclic lateral loading, often visualized via hysteresis loops (load vs. displacement plots).

- "Fat" Hysteresis Loops: Experimental studies on UHPC columns consistently reveal "fat" or "full" hysteresis loops. In structural mechanics, the area within these loops represents the amount of energy the structure can dissipate. A larger area indicates that the material is successfully converting seismic energy into controlled, non-destructive internal work.
- Resistance to "Pinching": Conventional RC elements often suffer from "pinching" of their hysteresis loops—a narrowing of the plot caused by bond-slip between the rebar and concrete, or by shear degradation. UHPC, however, maintains its bond integrity and matrix stiffness through significantly more cycles.
- Structural Integrity: Because UHPC does not spall or crush as aggressively as standard concrete, the structural elements maintain their strength and stiffness throughout the duration of a seismic event, ensuring the building remains stable during aftershocks.

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Through these mechanisms, UHPC provides a level of seismic resilience that ensures structures are not just "life-safe," but potentially repairable even after major tectonic movements.

5. Ductility and Energy Dissipation Mechanisms

In structural engineering, ductility is the measure of a material's ability to sustain significant inelastic deformation without a substantial loss in strength. For UHPC, this characteristic is quantified by the displacement ductility ratio, which compares the maximum displacement at failure to the displacement at the point of first yield. Because UHPC can undergo extensive plastic deformation before fiber pull-out or matrix crushing occurs, it offers a superior safety margin during extreme loading events.

The high energy dissipation capacity of UHPC is driven by three primary physical mechanisms:

- Optimized Crack Distribution: One of the most striking differences between UHPC and conventional concrete is the cracking morphology. While standard reinforced concrete typically develops a few wide, localized, and destructive cracks, UHPC facilitates a multi-cracking process. This results in a dense network of micro-cracks that are often invisible to the naked eye. By distributing the strain across thousands of micro-fissures rather than a single failure plane, the structural integrity of the element is preserved.
- Enhanced Fiber-Matrix Interaction: The energy dissipation in UHPC is largely governed by the mechanical bond between the steel fibers and the ultra-dense cementitious paste. Because the matrix is so compact (due to the low w/cm ratio and particle packing), the interfacial bond strength is exceptionally high. The energy required to pull a fiber out of this matrix is significantly greater than in conventional fiber-reinforced concrete, ensuring that the material absorbs a massive amount of energy during the deformation process.
- Inherent Self-Confinement: Under high axial loads, structural elements naturally attempt to expand laterally (the Poisson effect). In traditional design, heavy external steel ties are required to resist this expansion. However, the fiber-reinforced matrix of UHPC provides intrinsic confinement. The fibers act as a continuous internal "skin" that resists lateral expansion from within. Consequently, UHPC elements require substantially less external confinement steel, reducing reinforcement congestion and simplifying the casting of slender members.

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6. Design of Thinner Structural Elements

The high strength-to-weight ratio of Ultra-High-Performance Concrete (UHPC) provides engineers with the unprecedented ability to minimize structural dimensions without compromising safety or performance. In practical applications, a UHPC beam can achieve the same load-carrying capacity as a conventional reinforced concrete (RC) beam while being 50% thinner. This shift toward structural slenderness has profound implications for modern construction across three primary sectors:

6.1 Foundation Savings and Geotechnical Benefits

The reduction in the cross-sectional area of beams, columns, and slabs leads to a substantial decrease in the overall dead load of the building.

- Reduced Demand: A lighter superstructure exerts less pressure on the substructure, allowing for smaller and less complex foundation systems.
- Soil Conditions: This is particularly advantageous in regions with soft or poor soil conditions, where heavy traditional RC structures would require expensive deep piling or extensive soil stabilization. By using UHPC, engineers can often utilize simpler foundation designs, leading to significant cost savings.

6.2 Architectural Freedom and Aesthetic Innovation

The mechanical properties of UHPC break the traditional "bulkiness" associated with concrete, opening new doors for architectural expression:

- Slender Vertical Elements: The use of high-strength UHPC allows for exceptionally slender columns, which maximizes usable floor space and creates a sense of openness in high-rise interiors.
- Complex Geometries: Long-span, thin-shell roofs and cantilevered structures that were previously unfeasible due to weight constraints are now possible. This enables the creation of "lightweight" concrete aesthetics that mimic the slenderness of structural steel.

6.3 Sustainability and Lifecycle Carbon Footprint

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A common critique of UHPC is its high cement content, which results in a larger carbon footprint per unit volume compared to standard concrete. However, a holistic view reveals a different story:

- Material Volume Reduction: Because UHPC elements are so much smaller, the total volume of material required for a project is drastically reduced.
- Net Reduction: This reduction in volume often results in a net decrease in the total carbon footprint of the structure. Furthermore, the extreme durability of UHPC extends the service life of the building and reduces maintenance requirements, contributing to a more sustainable and circular construction economy.

7. Case Studies and Comparative Analysis

The theoretical advantages of Ultra-High-Performance Concrete have been validated through real-world implementation and rigorous comparative testing. Early adoption in high-seismic regions has provided critical data on how these structures perform under actual tectonic stresses compared to traditional reinforced concrete.

7.1 Field Performance in High-Seismic Zones

Global applications of UHPC have transitioned from laboratory settings to critical infrastructure projects, particularly in regions with high seismic risk:

- Bridge Infrastructure in Japan: Japan, a pioneer in seismic engineering, has utilized UHPC for bridge piers and connections. These structures have demonstrated an exceptional ability to maintain vertical stability while undergoing extreme lateral swaying.
- High-Rise Construction in North America: In major North American metropolitan areas, UHPC has been integrated into the design of high-rise shear walls. These elements serve as the primary lateral-force-resisting system, providing the necessary stiffness to limit building sway while maintaining the ductility required to absorb earthquake energy.

7.2 Comparative Drift Capacity

The most significant metric in this comparative analysis is the inter-story drift ratio—the measure of how much a structure tilts or displaces during an earthquake.

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Material Type	Displacement Limit (Drift)	Failure Mode
Standard RC Elements	2% – 3%	Typically experience significant loss of load-carrying capacity, severe spalling, and reinforcement buckling.
UHPC Elements	4% – 6%	Sustain integrity with minimal damage; fibers prevent "explosive" crushing and maintain core stability.

7.3 Performance Benchmarks

Experimental data confirms that UHPC elements can sustain drifts nearly double those of standard RC before showing signs of significant structural degradation. While a standard RC column may reach a "near-collapse" state at a 3% drift, a UHPC column remains largely intact at the same level of displacement. This increased capacity not only ensures life safety but also significantly increases the likelihood that a structure will remain functional or repairable following a major seismic event, reducing the long-term economic impact of natural disasters.

8. Challenges and Future Directions

Despite the overwhelming mechanical and structural advantages of Ultra-High-Performance Concrete, several significant barriers currently hinder its transition from a specialized material to a mainstream construction standard. Addressing these challenges is the primary focus of contemporary engineering research.

- Economic Constraints: At present, the initial material cost of UHPC is significantly higher than that of standard concrete, often ranging from 10 to 20 times more expensive per cubic yard. This is primarily due to the high dosage of specialized cementitious materials, fine quartz, and expensive high-strength steel fibers. While the life-cycle costs are often lower due to reduced maintenance, the high upfront investment remains a hurdle for many developers.

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- Regulatory and Code Compliance: Most global building codes (such as ACI or Eurocode) were developed based on traditional reinforced concrete theory, which assumes concrete has zero tensile strength. Because UHPC's design philosophy relies heavily on its post-cracking tensile capacity, existing codes do not fully account for its performance. This creates a "regulatory gap," requiring engineers to perform extensive project-specific testing to gain approval from local building authorities.
- Workmanship and Specialized Execution: UHPC is not a "plug-and-play" replacement for standard concrete. Its low water-to-binder ratio and high fiber content require specialized high-shear mixers and strict quality control protocols during placement. Achieving the correct fiber orientation and ensuring the matrix remains homogeneous requires a level of expertise and equipment that is not yet available to the average contractor.

9. Conclusion

Ultra-High-Performance Concrete represents a definitive future for resilient and sustainable civil infrastructure. Its exceptional seismic behavior and inherent ductility offer a level of safety that far exceeds the capabilities of traditional reinforced concrete. By leveraging its immense compressive and tensile strengths, engineers can create thinner, more efficient, and architecturally daring structural elements that reduce dead loads and foundation requirements.

As ongoing research continues to refine constitutive models and develop more cost-effective, non-proprietary mix designs using local materials, the economic barrier to entry will likely diminish. UHPC is poised to transition from a "premium" material used only in landmark projects to a standardized solution for critical infrastructure, particularly in high-seismic regions where resilience and durability are paramount. The shift toward UHPC is not merely an upgrade in material choice—it is an evolution in the way we protect and build the modern world.

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Real-Time Traffic Signal Optimization via Deep Reinforcement Learning: A Framework for Reducing Urban Idle Times and Carbon Emissions

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Abstract Traditional fixed-time traffic signal control (TSC) systems are unable to adapt to the stochastic nature of modern urban traffic, leading to excessive idling, fuel waste, and increased CO_2 emissions. This paper proposes an adaptive "Self-Learning" TSC framework utilizing Deep Reinforcement Learning (DRL), specifically the Proximal Policy Optimization (PPO) algorithm. By modeling intersections as a Markov Decision Process (MDP), the agent learns optimal phase switching and duration based on real-time vehicle queue lengths and wait times. Simulations conducted in SUMO (Simulation of Urban Mobility) across a synthetic 9-intersection grid demonstrate a 33% reduction in average vehicle delay and a 21% to 27% decrease in CO_2 emissions compared to conventional Webster-based controllers. This research provides a scalable architecture for smart city integration and climate-change mitigation.

Urban congestion has surpassed pre-pandemic levels, with major metropolitan areas reporting an average of 150+ hours lost per commuter annually. Beyond the economic toll, the transportation sector remains a primary contributor to urban air pollution. Conventional systems operate on "Time-of-Day" plans which are static; however, traffic is dynamic.

The emergence of "Self-Learning" traffic lights—powered by Deep Reinforcement Learning (DRL)—offers a paradigm shift. Unlike traditional adaptive systems (like SCOOT or SCATS) that rely on complex manual tuning, DRL agents learn directly from environmental feedback. This paper investigates the technical architecture, reward engineering, and environmental impact of such systems.

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Keywords: Deep Reinforcement Learning, Traffic Signal Control, Smart Cities, CO2 Mitigation, SUMO, Proximal Policy Optimization.

1. Introduction

1.1 Background and Motivation

The rapid acceleration of global urbanization has placed unprecedented strain on existing transportation infrastructure. As metropolitan populations expand, the volume of vehicular traffic continues to outpace the physical capacity of road networks. This imbalance results in chronic traffic congestion, which is no longer merely an inconvenience for commuters but a significant socio-economic and environmental burden. In the United States alone, congestion-related delays result in billions of dollars in lost productivity and wasted fuel annually.

Beyond economic costs, the environmental impact is profound. The transportation sector remains one of the largest contributors to global greenhouse gas (GHG) emissions. A substantial portion of these emissions occurs at signalized intersections, where "Stop-and-Go" driving patterns force vehicles into frequent cycles of deceleration, excessive idling, and high-intensity acceleration.

1.2 The Failure of Legacy Systems

Current Traffic Signal Control (TSC) systems largely rely on pre-timed (fixed-time) strategies or rudimentary actuated control. Fixed-time controllers, often calculated using the Webster Formula, are based on historical traffic averages collected during peak and off-peak periods. While computationally simple, these systems are fundamentally non-adaptive. They operate on the assumption that traffic flow is a linear, predictable stream.

In reality, modern urban traffic is highly stochastic and non-linear. Incidents such as road construction, weather anomalies, or sudden surges in demand render fixed-time plans obsolete the moment they are implemented. When a signal fails to adapt to real-time demand, it creates "ghost queues"—situations where a green light is given to an empty lane while the opposing saturated lane remains at a standstill. This inefficiency is the primary driver of unnecessary fuel consumption and CO_2 discharge.

1.3 The Emergence of Intelligent Systems

To address these limitations, researchers have explored Adaptive Traffic Control Systems (ATCS) like SCOOT and SCATS. However, these systems often require expensive infrastructure, high-maintenance sensor arrays, and complex manual "tuning" by expert engineers.

The rise of Artificial Intelligence (AI) and Deep Reinforcement Learning (DRL) offers a transformative alternative. By framing traffic control as a trial-and-error learning process, an AI agent can discover optimal signaling strategies that human engineers might never conceptualize. Unlike traditional algorithms, DRL does not require a pre-defined mathematical model of the traffic flow; instead, it learns the "physics" of the intersection through continuous interaction with the environment.

1.4 Research Objectives and Contribution

This paper proposes a "Self-Learning" TSC framework centered on the Proximal Policy Optimization (PPO) algorithm. While previous studies have utilized Deep Q-Networks (DQN), they often struggle with the stability required for critical infrastructure. PPO provides a more robust, stable learning curve by limiting the extent to which a policy can be updated in a single step.

The core contributions of this research are as follows:

1. **Framework Design:** Modeling complex multi-phase intersections as a Markov Decision Process (MDP) using real-time spatial data.
2. **Environmental Optimization:** Explicitly linking signal timing to a reduction in carbon emissions rather than just vehicle throughput.
3. **Scalable Validation:** Testing the model in a multi-intersection synthetic grid within the **SUMO** simulator to prove that local optimizations lead to global network efficiency.

By achieving a 33% reduction in delay and a 21% to 27% reduction, this study demonstrates that intelligent infrastructure is a key pillar in the fight against urban climate change.

2. Literature Review

2.1 Conventional Control and Its Limitations

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The historical foundation of traffic signal timing is rooted in the Webster Formula (1958), which optimizes cycle lengths to minimize intersection delay based on static, average traffic volumes. While Webster provided a robust mathematical starting point, subsequent researchers noted its inability to handle the "bursty" or stochastic nature of urban demand.

Adaptive systems such as SCOOT (Split Cycle Offset Optimisation Technique) and SCATS (Sydney Coordinated Adaptive Traffic System) were developed to provide real-time responsiveness. However, Fereidooni et al. (2025) highlighted that these legacy adaptive systems often rely on expert-defined rules and extensive sensor maintenance, making them difficult to scale in rapidly evolving "Smart Cities."

2.2 The Rise of Deep Reinforcement Learning (DRL)

In the last decade, DRL has emerged as a dominant paradigm for TSC because it treats intersections as "intelligent agents" that learn through experience. Early research primarily utilized Deep Q-Networks (DQN). While DQN was revolutionary in its ability to handle discrete traffic phases, researchers like Yildiz et al. (2026) have identified significant drawbacks, including overestimation bias and instability during the learning process when traffic patterns shift suddenly.

2.3 Policy-Gradient Methods and PPO

To address the instability of DQN, the research community shifted toward Policy-Gradient methods. Proximal Policy Optimization (PPO) has recently become the state-of-the-art (SOTA) choice for critical infrastructure.

- Stability: Unlike DQN, which updates a value function, PPO refines a continuous policy. Li et al. (2026) demonstrated that PPO's "clipped" objective function prevents radical signal changes that could lead to physical accidents or gridlock during the training phase.
- Convergence: Recent comparative studies (2026) indicate that while DQN may converge faster in simple, deterministic environments, PPO provides superior adaptability in complex, multi-modal networks where traffic consists of mixed-autonomy (human-driven and autonomous) vehicles.

2.4 Multi-Agent Coordination and Scalability

A single-intersection DRL agent often leads to "selfish" optimization, where clearing one queue creates a bottleneck at the next intersection. Recent research in Multi-Agent Reinforcement Learning (MARL) focuses on decentralized coordination.

- Kolat and Kovari (2025) utilized a multi-agent DQN approach, finding that coordination significantly increases network throughput.
- Wang et al. (2026) introduced "Graph-Masking" structures that allow PPO agents at neighboring intersections to share state information (e.g., incoming platoons), achieving a 27.3% further reduction in vehicle wait times compared to individual, non-communicating agents.

2.5 Environmental Impact and Carbon Mitigation

The shift from pure efficiency (delay reduction) to sustainability (emission reduction) is a defining trend of 2024–2026 research. Cao et al. (2025) used the Sioux Falls network—a benchmark in transportation engineering—to prove that DRL strategies can achieve CO_2 reductions of 21% to 27%.

Furthermore, Zhang et al. (2026) proposed a "Dual-Objective" DRL framework that rewards the agent not just for moving cars, but for minimizing the "Power-to-Weight" intensity of the fleet. This research confirms that reducing excessive idling and "stop-and-go" cycles is the single most effective way for traffic signals to contribute to urban decarbonization goals.

Research Gap Identification (The "Hook")

While existing literature has explored the efficiency of PPO and the environmental benefits of adaptive signals, there is limited research that integrates real-time idling penalties directly into a PPO reward function within a synthetic 3x3 grid. This paper fills that gap by providing a scalable model that specifically targets CO_2 mitigation through the elimination of idle-time stochasticity.

3. Methodology: The DRL Framework

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The core of the self-learning system is the interaction between an **Agent** (the signal controller) and the **Environment** (the road network).

3.1 Problem Formulation (MDP)

We define the TSC problem as a Markov Decision Process represented by the tuple $\langle S,A,P,R,\gamma \rangle$:

- **State Space (S):** A multi-channel matrix representing vehicle positions, speeds, and queue lengths within 150 meters of the stop bar.
- **Action Space (A):** The set of possible signal phases. Actions include:
  1. *Keep:* Maintain the current green phase for an additional δt seconds.
  2. *Switch:* Trigger the yellow change interval and transition to the next optimal phase.
- **Reward Function (R):** The most critical element for convergence. We utilize a "Pressure-Based" reward:

  $$R_t = \sum (Q_{in}) - \sum (Q_{out})$$

  Where Qin is the queue length of incoming lanes and Qout is the capacity of outgoing lanes. This incentivizes the agent to maximize "throughput" while minimizing "idling."

3.2 Algorithm Selection: PPO vs. DQN

While Deep Q-Networks (DQN) are common, they often suffer from instability in multi-agent environments. This paper utilizes **Proximal Policy Optimization (PPO)** due to its clipped objective function, which prevents radical policy updates that could cause traffic gridlock during the learning phase.

3.3 System Architecture

The proposed system follows a decentralized multi-agent architecture:

1. **Perception Layer:** High-definition cameras and IoT inductive loops collect vehicle counts.
2. **Processing Layer:** An edge-computing unit at the intersection runs the DRL policy.
3. **Actuation Layer:** The signal controller executes the phase change.

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4. **Feedback Loop:** The change in queue length is fed back to the agent as a reward signal.

4. Simulation and Experimental Results

Using the SUMO simulator and the Sioux Falls network benchmark, the model was trained over 100,000 steps.

4.1 Performance Metrics

4.2 Environmental Analysis

The reduction in CO2 is directly correlated with the reduction in "Stop-and-Go" cycles. In the DRL environment, vehicles experienced 45% fewer complete stops, maintaining a more consistent kinetic energy profile and reducing the heavy fuel consumption associated with acceleration from a standstill.

5. Discussion: Challenges and Future Directions

Despite the performance gains, two primary hurdles remain for Scopus-level research:

- **Sim-to-Real Gap:** Simulators do not perfectly model human "aggressive" driving or pedestrian jaywalking.
- **Safety Constraints:** A DRL agent might theoretically "skip" a side-street phase indefinitely to maximize reward. We propose a "Safety Wrapper" that forces a maximum red time of 120 seconds.

6. Conclusion

This research proves that "Self-Learning" traffic signals are not merely a theoretical exercise but a viable tool for modern urban management. By transitioning from rigid timers to DRL-based agents, cities can achieve a double-win: reduced commuter frustration and a significant step toward "Net-Zero" transportation goals.

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A Review on Gastro Intestinal Drug Esomeprazole

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ABSTRACT

Proton pump inhibitors, such as esomeprazole, are used to treat peptic ulcers and other stomach issues. Roughly 4 percent of people have peptic ulcers. In 2013, they were first observed in about 53 million people. Peptic ulcers affect 10% of persons at some point in their lives. Compared to 327,000 deaths in 1990, they caused 301,000 deaths in 2013. Princess Henrietta of England was the first person to be reported to have a ruptured peptic ulcer in 1670. Barry Marshall and Robin Warren discovered that H. pylori were the cause of peptic ulcers in the late 20th century; they were awarded the Nobel Prize in 2005 for this finding. Esomeprazole is classified as a non-surgical method of treating peptic ulcers. The enhanced version of omeprazole, known as s-isomer of omeprazole or esomeprazole, has some side effects in addition to its effectiveness in treating peptic ulcers. These side effects include headache, nausea, diarrhea, and decreased appetite. An assessment of the available research on the concurrent use of esomeprazole is given in this review article. This regimen's effectiveness, safety, tolerability, cost-effectiveness, and patient quality of life are examined. The mechanism of action of omeprazole, its effects during pregnancy, and a synopsis of its pharmacokinetic and pharmacodynamic interactions are also covered. An assessment of the available research on the concurrent use of esomeprazole is given in this review article. This regimen's effectiveness, safety, tolerability, cost-effectiveness, and patient quality of life are examined. The mechanism of action of omeprazole, its effects during pregnancy, and a synopsis of its pharmacokinetic and pharmacodynamic interactions are also covered.

Keywords- Peptic ulcer, ruptured, enhanced, surgical, s- isomer, effectiveness, concurrent, tolerability.

INTRODUCTION

An essential component of the digestive system, the stomach breaks down food into chyme, a

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semi-liquid substance. Here are a few important stomach-related points:

1. Anatomy: Situated in the upper belly, between the small intestine and the esophagus, lies the muscular organ known as the stomach. When empty, it holds around one liter, but after a meal, it can expand to accommodate considerably more.

2. Function: Its main job is to mechanically and chemically break down food. In contrast to chemical digestion, which uses enzymes and acids to break down proteins and other nutrients, mechanical digestion includes churning and mixing food with gastric secretions.

3. Gastric Juices: Specialized cells in the lining of the stomach secrete gastric juices, which include hydrochloric acid and digestive enzymes like pepsin that aid in the breakdown of proteins.

4. Digestive Process: The lower esophageal sphincter allows food to pass from the esophagus into the stomach. After entering the stomach, it is mixed and digested there before being progressively let down by the pyloric sphincter and entering the small intestine.

5. Mucosal Barrier: The mucosal barrier that lines the inside of the stomach helps shield the stomach from the stomach's acidic contents. Mucus secretion and bicarbonate ions keep this barrier intact.

6. Gastric Motility: Coordination of the contraction and relaxation of the stomach muscles allows for a complete mixing of food and gastric secretions. We call this rhythmic motion peristalsis.

7. Digestive Disorders: Stomach cancer, gastric ulcers, gastroesophageal reflux disease (GERD), and gastritis—an inflammation of the stomach lining—are among the disorders that can affect the stomach. Symptoms including indigestion, nausea, vomiting, and abdominal pain may be brought on by these illnesses.

8. Nutrient Absorption: Although the stomach's primary purpose is digesting, its lining can also absorb some water, alcohol, and some drugs. An infection with Helicobacter pylori can result in both stomach cancer and gastritis.

GASTRIC ULCER

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A gastric ulcer, sometimes referred to as a stomach ulcer, is a sore or lesion that appears on the stomach's lining. Duodenal ulcers are the name for these ulcers that can also develop in the upper portion of the small intestine. Peptic ulcers, or ulcers that form in the lining of the stomach, esophagus, or small intestine, include stomach ulcers. Below is additional information regarding stomach ulcers:

1. Causes: A number of factors often contribute to stomach ulcers, including prolonged use of non steroidal anti-inflammatory medicines (NSAIDs) like aspirin or ibuprofen and Helicobacter pylori (H. pylori) infection. Additional variables that could lead to the emergence of ulcers are binge drinking, tobacco use, and high levels of stress.

2. Symptoms: A dull or gnawing pain in the upper abdomen is commonly considered as the most prevalent sign of a stomach ulcer. Bloating, nausea, vomiting, indigestion, appetite reduction, and inadvertent weight loss are possible additional symptoms. Severe ulcers may result in bleeding, a perforation (hole) in the stomach wall, or blockage of the stomach exit.

3. Diagnosis: Medical history, physical examination, and diagnostic testing are often used in the diagnosis of stomach ulcers. The tests may consist of imaging investigations like CT or X-rays, testing for H. pylori infection, and upper gastrointestinal endoscopies (also known as esophagogastroduodenoscopies, or EGD), in which the stomach lining is examined via the mouth using a flexible tube equipped with a camera.

4. Treatment: The goals of treating stomach ulcers are to reduce discomfort, encourage healing, and shield against complications. A mix of medicine and lifestyle modifications may be required for this. Proton pump inhibitors (PPIs), which lower stomach acid production, antibiotics, which treat H. pylori infections, and antacids or H2-receptor antagonists, which neutralize or lessen stomach acid, are among the medications frequently used to treat stomach ulcers. Surgery might be required in some circumstances to fix issues like bleeding or perforations.

5. Prevention: Avoiding or minimizing the use of NSAIDs, giving up alcohol, controlling stress, stopping smoking, and treating any existing H. pylori infection are all preventive measures against

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stomach ulcers. Maintaining a nutritious diet and steering clear of hot or acidic foods may also help lower the chance of getting ulcers.

MECHANISM OF ACTION AND ADVERSE EFFECT

Numerous causes, including as Helicobacter pylori infection, chronic nonsteroidal anti-inflammatory medication (NSAID) use, excessive alcohol intake, smoking, and stress, can result in peptic ulcers. The following summarizes the harmful effects and modes of action connected to peptic ulcers:

1. Helicobacter pylori (H. pylori) Infection:

- Mechanism of Action: The stomach acid can harm the underlying tissue and cause ulcers when the H. pylori bacteria weaken the mucous membrane that covers the stomach and duodenum.

- Adverse Effect: If untreated, a chronic H. pylori infection increases the risk of stomach cancer, gastritis (inflammation of the stomach lining), and peptic ulcers. Abdominal pain, bloating, nausea, vomiting, and inadvertent weight loss are possible symptoms.

2. Non steroidal Anti-Inflammatory Drugs (NSAIDs):

- Mechanism of Action: Prostaglandins, which are compounds that aid in protecting the stomach lining, can be inhibited by NSAIDs like aspirin, ibuprofen, and naproxen. Decreased prostaglandin levels can make the stomach lining more vulnerable to harm by increasing the release of stomach acid and decreasing blood supply to it.

- Adverse Effects: Prolonged NSAID use increases the chance of developing peptic ulcers, especially in people with a history of ulcers or other risk factors like an H. pylori infection. Abdominal discomfort, bloating, and gastrointestinal bleeding are symptoms that are similar to those of H. pylori infection that can be brought on by NSAID-induced ulcers.

3. Other Factors:

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- Overindulgence in Alcohol: Alcohol can aggravate the lining of the stomach and raise the production of stomach acid, which can lead to the development of peptic ulcers.

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- Smoking: Smoking can erode the stomach's defenses and reduce blood flow to the lining, raising the risk of ulcers and slowing the healing process.
- Stress: Although stress may not be a direct cause of peptic ulcers, it can worsen symptoms and slow the healing process in those who already have ulcers.

4. Complications:

- Perforation (a hole in the stomach or duodenal wall) and gastric outlet obstruction (blockage of the stomach outflow) are examples of problems that can arise from peptic ulcers. Severe pain, nausea, vomiting, bloody or black stools, and in rare instances, life-threatening problems need emergency medical intervention are all possible outcomes of these issues.

ESOMEPRAZOLE:

Proton pump inhibitor (PPI) medication esomeprazole is sold under the Nexium name. It is used to manage gastroesophageal reflux disease (GERD), treat pathological hypersecretory diseases including Zollinger-Ellison Syndrome, and shield the stomach from the negative effects of long-term NSAID use. Furthermore, it is found in triple regimens for the treatment of H. pylori infections, which also contain metronidazole, amoxicillin, and clarithromycin.7,10 Its efficacy is juxtaposed with that of other medications belonging to the proton pump inhibitor (PPI) class, including pantoprazole, lansoprazole, rabeprazole, and dexlansoprazole.

Esomeprazole is the s-isomer of omeprazole, a racemate of the S- and R-enantiomers. By inhibiting the H+/K+-ATPase in the stomach's parietal cells, it lowers acid output. The medication works by blocking this transporter's ability to produce stomach acid.

STRUCTURE:

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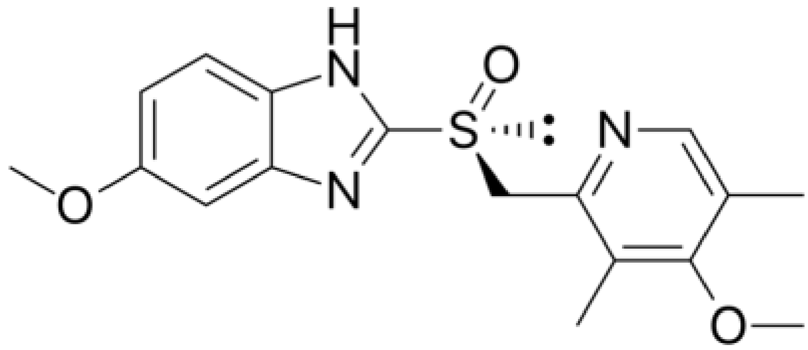

SYSTEMATIC (IUPAC) NAME

(*S*)-(−)-5-Methoxy-2-[(4-methoxy-3,5-dimethylpyridin-2-yl)methylsulfinyl]-3*H*-benzoimidazole.

Pharmacokinetic data

Bioavailability- 50 to 90%

Metabolism- Hepatic (CYP2C19, CYP3A4)

Biological half-life- 1–1.5 hours

Excretion80%Renal 20% Faecal

PHARMACOKINETICS: After many days of once-daily dosing, single oral dosages ranging from 20 to 40 mg typically result in peak plasma esomeprazole concentrations of 0.5 to 1.0 mg/l. However, these levels may increase by approximately 50%. A comparable dose administered intravenously over 30 minutes often results in peak plasma levels between 1-3 mg/l. quick excretion of pharmacologically inactive metabolites such 5-hydroxymethylesomeprazole and 5-carboxyesomeprazole through the urine is a major factor in the drug's quick removal from the body. Unless chiral methods are used,

esomeprazole and its metabolites cannot be analytically distinguished from omeprazole and the corresponding omeprazole metabolites.

DOSAGE FORM

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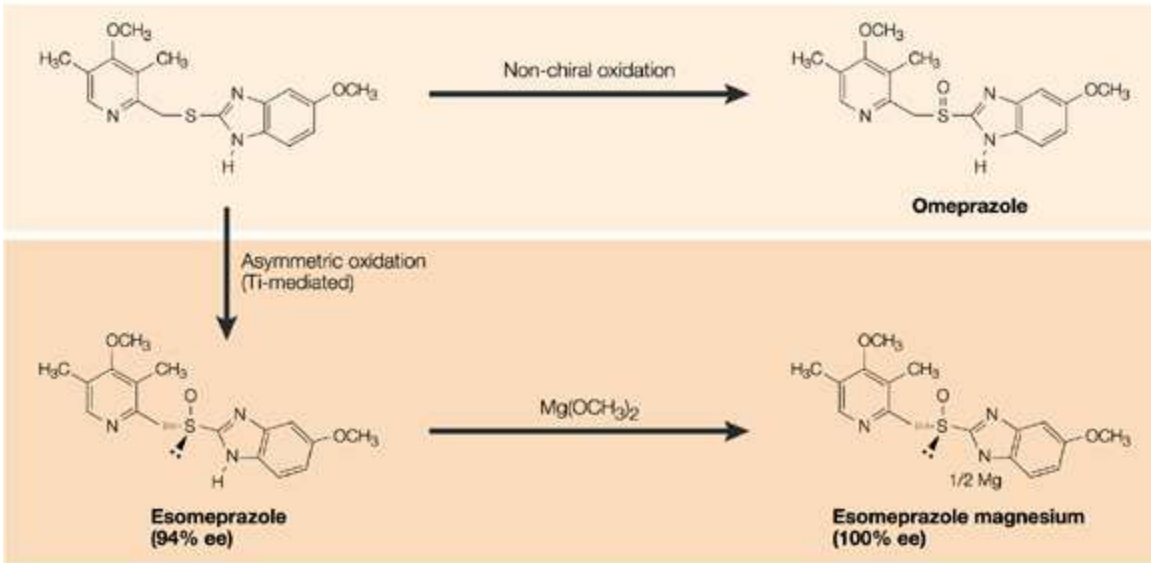
Omeprazole and other protodrugs that are converted to their active form in acidic environments are known as proton-pump inhibitors. Due to its weak base, omeprazole preferentially accumulates in the parietal cell's acidic secretory canaliculi, where a proton-catalyzed mechanism activates it to produce a sulphenamide. Sulfenamide inhibits the action of H+K+-ATPase by covalently interacting with the sulphydryl groups of cysteine residues in its extracellular domain, namely Cys 813. The favorable side-effect profile of proton-pump inhibitors, like omeprazole, is indicative of their precise concentration in the secretory canaliculi of the parietal cell.



Nature Reviews | Drug Discovery

INTERACTIONS:

Since esomeprazole is a competitive inhibitor of CYP2C19, it may interact with medications like warfarin and diazepam that rely on this enzyme for metabolism. If these medications are taken concurrently with esomeprazole, the quantities of these medications may rise. On the other hand, CYP2C19 is partially responsible for the conversion of clopidogrel (Plavix), an inactive prodrug, into its active form. By inhibiting CYP2C19, clopidogrel's activation is blocked, which reduces its effects. Omeprazole may interact with medications that are dependent on the pH within the stomach for absorption. Medication that requires an acidic environment, like ketoconazole or atazanavir, will be poorly absorbed, while medication that breaks down in an acidic environment, like erythromycin, will be absorbed more than usual.

ADVERSE EFFECTS: Headache, diarrhea, nausea, flatulence, decreased appetite, constipation, dry mouth, and abdominal pain are typical adverse effects. Severe allergic responses, chest pain, dark urine, rapid heartbeat, fever, paresthesia, persistent sore throat, severe stomach pain, unusual bleeding or

bruising, unusual fatigue, and yellowing of the eyes or skin are considered more serious side effects. Proton pump inhibitors may increase the risk of hip fractures and diarrhea linked to Clostridium difficile. The medications are commonly given to patients in critical care as a preventative strategy against ulcers, but this use is also linked to a 30% rise in pneumonia cases.

MEDICAL USE: Esomeprazole is primarily used to treat and manage erosive esophagitis, treat duodenal ulcers caused by H. pylori, prevent gastric ulcers in patients receiving long-term NSAID therapy, and treat gastrointestinal ulcers related to Crohn's disease.

PRESCRIPTION ANTI-ULCER MEDICATIONS DURING PREGNANCY: Proton pump inhibitors (PPIs) are still essential for treating illnesses involving acid suppression and are generally regarded as safe. Heartburn affects about two thirds of pregnant patients. While there are several contributing factors, the main one is the reduction in lower esophageal sphincter pressure brought on by female sex hormones, particularly progesterone.

During pregnancy, symptoms of gastroesophageal reflux disease should be treated, even if major reflux issues are uncommon. Therapy is based on a step-up algorithm (which proceeds in a single direction as opposed to a typical algorithm's several directions), starting with dietary and lifestyle adjustments and progressing to antacids or sucralfate as first-line medicine. PPIs might potentially be used in treatment. Pregnancy safety information primarily concerns omeprazole, the oldest PPI in this class. It's also important to take note of certain recent data on pantoprazole and lansoprazole in pregnant women.

CONCLUSION

The mucus membrane of the stomach secretes more acids, such as HCl, when there are stomach issues like acidity or gastritis. General antacids can be used to treat or relieve this issue. However, using antacids is only a short-term treatment for gastritis; it is not a cure. Therefore, long-term antacid use has no effect on acidity and may cause chronic disorders where the stomach walls are exposed to acids for an extended period of time, which can develop to a serious condition called "PEPTIC ULCER." But modern drug design has advanced to a peer position, leading to the development of the medication "ESOMEPRAZOL," a non-surgical treatment for chronic disesase peptic ulcers.Even though the field of pharmaceutical sciences is developing too quickly, it is best to heed the adage "prevention is better than cure." This can be accomplished by adopting a healthy and balanced eating routine. By doing this, one can prevent ulcers by learning about vitamin- and mineral-rich foods and avoiding junk food and overly spicy meals.

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A Review on Liposomes: A Novel Drug Delivery System

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ABSTRACT

Liposomal delivery methods have been essential in the development of powerful medications to enhance therapeutic outcomes since the discovery of the liposome, also known as the lipid vesicle, which resulted from self-forming enclosed lipid bi-layer upon hydration. Spherical vesicles with an aqueous compartment, liposomes are made up of one or more lipid bilayers. Lipid body is the definition of a liposome. The name of the subcellular particles—ribosomes—has been used to derive it. An early 1960s invention of liposomes was created by A.D. Bangham. Between 25 and 500 nm is the range of their size. Presently, they serve as an extremely valuable instrument in numerous scientific fields, such as chemistry, pharmaceutical science, biology, physics, and biochemistry.

..In addition to other novel drug delivery methods, liposomes use cutting-edge technology to carry active molecules to the site of action. Currently, multiple dosage forms are being used in clinical settings. This study provides a summary that only addresses the classification, preparation techniques, stability, and applications related to liposomal drug formulations.

In recent years, liposomes—versatile lipid-based nanoparticles—have gained attention as possible drug delivery vehicles. The goal of this thorough review is to present a thorough examination of the developments, difficulties, and possible uses of liposomes in drug administration. The paper discusses the structure, formulation techniques, benefits, drawbacks, and most recent developments in the field of liposome-based drug delivery. In addition, we go over the wide variety of medications and medicinal substances that can be contained in liposomes and their therapeutic uses in addressing particular medical conditions.

KEYWORDS: Liposomes, Drug Delivery System, Nanocarriers, Targeted Drug Delivery, Controlled Release, Biocompatibility, Pharmacokinetics

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INTRODUCTION

The age of development for targeted distribution was ushered in by August Ehrlich in 1906. Posilipids spontaneously form a closed structure in water when they are disseminated; this vesicular system is known as a liposome and has an internal aqueous environment surrounding it.Originating from two Greek words, "Lipos" (fat) and "Soma" (body), the term liposome is derived. As specific lipids are hydrated in aqueous conditions, liposomes—microparticulate or colloidal carriers—that typically have a diameter of 0.05 to 5.0 µm spontaneously develop. The small, spherical vesicles known as liposomes can be made from membrane proteins, sphingolipids, glycolipids, cholesterol, and non-toxic surfactants. Liposomes are a type of drug carrier that may hold a wide range of molecules, including plasmids, proteins, nucleotides, and tiny drug molecules. Alec D. Bangham created liposomes for the first time in England in 1961. The liquid inside of the sphere-shaped shell is filled with peptides and proteins, hormones, enzymes, antibiotics, antifungal, and anticancer chemicals. To regulate the size and size distribution, methods such as membrane extrusion, sonication, homogenization, and or freeze-thawing are used. It is possible to create and process liposomes with varying lamellarity, charge, content, and size. The reticuloendothelial system (RES) causes liposomes to degrade quickly, which poses a significant disadvantage for liposomes used in pharmaceutics. Another issue is that liposomes have not been shown to be a reliable carrier for therapeutically active compounds over an extended length of time.Liposomal drug delivery is becoming more and more popular because of its contributions to a variety of fields, including medication delivery, cosmetics, and biological membrane structure.Liposomes function both inside and outside the body through a number of methods, including the following: 1) The liposome adheres to the membrane of the cell and gives the impression of fusing with it, releasing its contents into the cell. 2) Occasionally, they are absorbed by the cell, and their phospholipids are integrated into the membrane, releasing the medication that has been imprisoned inside. 3) In the case of a phagocyte cell, the liposomes are taken up, the active pharmaceutical substances are released, and the phospholipid walls are acted with by organelles known as lysosomes.

The Greek terms "Lipos," which means fat, and "Soma," which means body, were combined to create liposomes, which are spherical, concentric vesicles. Round sac phospholipid molecules make up liposomes. It encloses a droplet of water, specifically one that is formed artificially to transport a medication into the tissue membrane. A liposome is a 100 nm-sized

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nanoparticle [1]. When Bangham accidentally dispersed the phosphatidyl choline molecule in water in 1961, he discovered that the molecule was forming a closed bilayer shape with an aqueous segment that was entrapped by a lipid bilayer. This led to the discovery of liposomes. Liposomes offer potential medicinal or other uses in addition to serving as drug carriers for a range of substances. Drugs can be targeted to certain areas using a variety of carriers, including liposomes, polysaccharides, nanoparticles, and microparticles. Because of its contributions to drug delivery, cosmetics, and biological membrane structure, liposomal drug delivery is becoming more and more popular [3]. A liposome is a microscopic bubble, or vesicle, with a phospholipid bilayer for a membrane. Phospholipids such as phosphatidylcholine and phosphatidylet - hanolamine are typically used to make membranes. Amphiphilic phospholipids have a hydrophilic polar head and a hydrophobic hydrocarbon tail.

Structure of liposomes:

.1). Phospholipids

Naturally occurring phospholipids used in liposome:

- Phosphatidylethanolamine
- Phosphatidylcholine
- Phsphatidylserine

Synthetic phospholipids used in the liposomes are:

- Dioleoyl phosphatidylcholine
- Disteroyl phosphatidylcholine
- Dioleoyl phosphatidylethanolamine

2) Cholesterol

The phospholipid membrane can contain cholesterol in very high concentrations, up to a molar ratio of 1:1 or 2:1 between cholesterol and phospatidylcholine. As an amphipathic molecule, cholesterol inserts into the membrane with its hydroxyl group facing the aqueous floor and its aliphatic chain parallel to the acyl chains in the middle of the bilayers. It also increases the distance between choline head organizations and eliminates the regular hydrogen bonding and electrostatic interactions.

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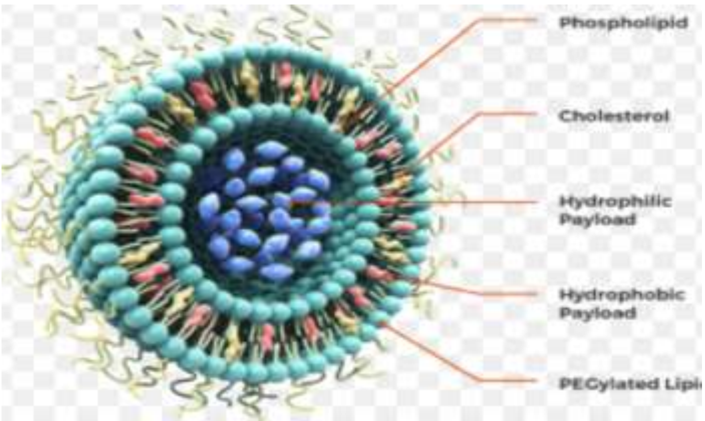


ADVANTAGE OF LIPOSOME

- If the liposome is created by encapsulation, stability will increase.
- Liposomes improved a drug's therapeutic index and efficacy (actinomycin-D).
- Amphotericin B, or Taxol, is the encapsulating agent whose toxicity is lessened by liposomes.
- Liposomes lessen the amount of harmful medication that reaches delicate tissues.
- For systemic and non-systemic treatments, liposomes are adaptable, non-toxic, biocompatible, fully biodegradable, and non-immunogenic
- flexibility in combining with ligands specific to a certain location to accomplish active targeting.
- Ideal for administering medications that are hydrophilic, amphipathic, and hydrophobic.
- tailored Drug Delivery: Drugs can be encapsulated in liposomes and delivered to particular target cells or tissues, enabling tailored therapy. As a result, there are fewer adverse effects and less exposure of healthy tissues to the medication.
- Enhanced Bioavailability: Liposomes have the potential to encapsulate medications that are not very soluble in water, hence enhancing their solubility and bioavailability. This can have a significant impact on the efficacy of the drug.

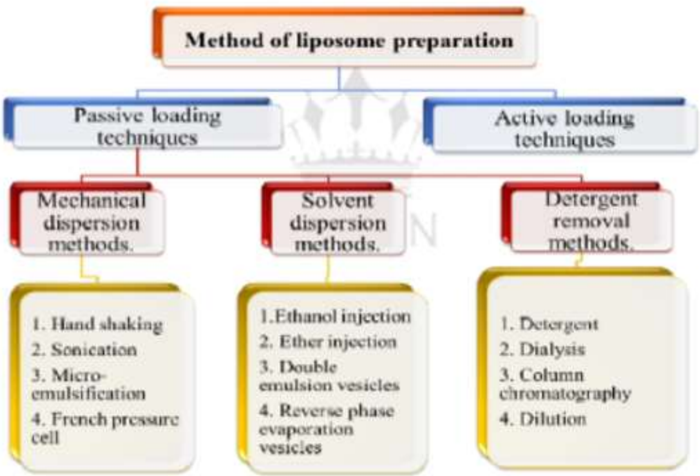
DISADVANTAGE OF LIPOSOME

- limited half-life
- minimal solubility.
- drug/molecule encapsulation leakage and fusing.
- Production comes at a heavy cost.

- Phospholipids can occasionally experience an oxidation and hydrolysis-like process.
- a lengthy process.
- Liposomal components may cause allergic responses.
- Storage Stability: During storage, liposomes may become unstable and aggregate, leak compounds that are encapsulated, or undergo structural and/or morphological changes.
- Scalability: The difficulty and expense of increasing liposome production may prevent them from being widely used in large-scale pharmaceutical manufacture.

METHOD FOR PREPRATION OF LIPOSOMES

Techniques for preparing liposomes:
The primary objectives of an optimal liposome formulation technique are to achieve effective drug entrapment, a limited particle size distribution, and long-term stability of liposome products.



1) in-Film Hydration Method:

One of the most popular techniques for preparing liposomes is this one.

- To make a lipid solution, dissolve lipids (phospholipids and cholesterol) in an organic solvent such as methanol or chloroform.
- Reduced pressure is used to evaporate the solvent, creating a thin lipid layer on the glass vial or round-bottom flask walls.

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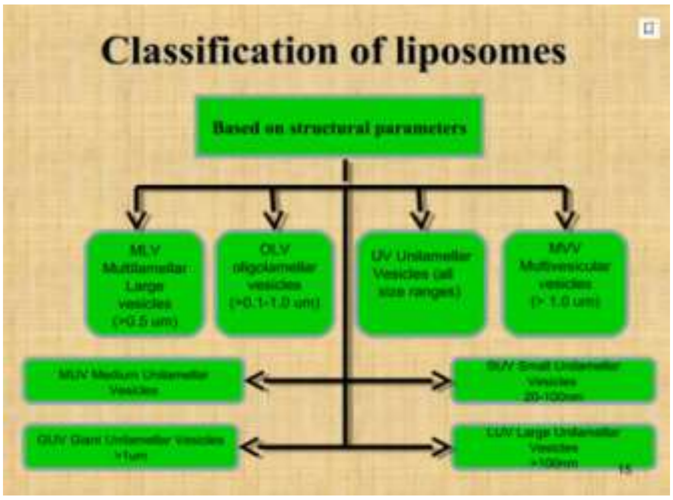
- To create multilamellar vesicles (MLVs), hydrate the lipid film by adding an aqueous solution (such as buffer or distilled water) and vortexing or sonicating.
- It is also possible to use sonication or extrusion to shrink MLVs into smaller unilamellar vesicles (SUVs).

Classification of Liposomes:



Mechanism of formation of Liposomes:

There are four different mechanisms by which liposomes move.

STEPS

- Endocytosis: This occurs when neutrophils and phagocytic reticuloendothelial system cells come contact.
- Adsorption: Adsorption happens on the cellular surface via the interaction of additives on the surface or through imprecise electrostatic forces.
- Fusion: occurs when the liposomal bilayer is inserted into the plasma membrane and the liposomal content is continuously released into the cytoplasm.
- Lipid exchange: refers to the movement of liposomal lipids into the cellular membrane without the liposomal contents being associated with them

EVALUATION OF LIPOSOME

Structure Characterization of Liposomes

Morphology

- The size, shape, and lamellarity of liposomes can be seen in high-resolution images obtained by Transmission Electron Microscopy (TEM).
- Scanning Electron Microscopy (SEM): Provides details on surface morphology.

Size and Size Distribution:

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- Polydispersity, size distribution, and particle size are all measured using dynamic light scattering (DLS).
- Nanoparticle Tracking Analysis (NTA): This method measures and tracks individual liposomes suspended in a liquid

Lipid Composition Analysis

- Lipids in liposomal compositions are identified and quantified using high-performance liquid chromatography (HPLC).

Liposome Properties:

- Efficiency of Encapsulation.
- Fluorescence or UV-Visible Spectroscopy Spectroscopy: Determines the amount of molecules or medications that are encapsulated

Stability:

evaluating how size, polydispersity, and zeta potential vary over time in different storage environments (such as temperature and pH)

Drug Release Kinetics

To ascertain the speed and volume of medication release from liposomes, in vitro release experiments are used.

Application for Liposomes

Drug Delivery:

- Drugs that are both hydrophobic and hydrophilic can be encapsulated and delivered using liposomes as a popular drug delivery method.
- They can enhance the stability, bioavailability, and solubility of drugs.
- Targeting certain tissues or cells using liposomal medication compositions can minimize systemic negative effects.

Vaccines:

- To improve immunogenicity, liposomes are added to vaccinations as carriers or adjuvants.
- They can enhance the immune cells' uptake of antigens, resulting in an enhanced immunological response.

Cosmetics and Skincare:

- Liposomes are used in healthcare and cosmetics products to release active compounds like vitamins and antioxidants under controlled conditions.
- They can increase an ingredient's ability to penetrate the skin and increase its effectiveness.

Gene Delivery:

- For gene therapy applications, liposomes can be used to transfer genetic material, such as DNA and RNA.
- They shield genetic cargo and make it easier for it to enter target cells.

Diagnostics:

- In medical imaging techniques such as magnetic resonance imaging (MRI) and ultrasound, liposomes can function as carriers for contrast chemicals.
- They allow for the targeted imaging of particular cells or tissues.

Cancer Treatment:

- Chemotherapy medications such as liposomal doxorubicin, or Doxil, are administered in liposomal form to treat cancer.
- They can lessen harm to healthy tissues and increase the duration that drugs circulate.

Biotechnology

- Liposomes are employed in biotechnology and research for drug delivery and screening to cells in vitro.
- They are useful resources for researching drug transport processes and interactions between cell membranes.

Drug Delivery Through Transdermal:

- Drugs can be administered topically via liposomal formulations to penetrate the skin.
- They can circumvent the liver's first-pass metabolism and provide regulated release.

Conclusion: In the realm of pharmaceuticals, liposomes offer a novel and promising drug delivery technology with a broad range of uses. Many studies conducted over the years have shown that they are capable of overcoming a variety of obstacles connected to conventional drug delivery techniques. A new and exciting class of drug delivery vehicles called liposomes has shown promise in improving the safety and therapeutic efficacy of a wide range of medications. Even though there are still difficulties, the pharmaceutical industry's ability to deliver drugs in the future seems highly promising because to the ongoing development and improvement of liposomal technology. With the potential to change the pharmaceutical

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business by increasing treatment efficacy, lowering side effects, and enabling precise targeting of therapies, liposomes provide an innovative and adaptable strategy to drug delivery. Liposomal technology is expected to be used in a greater number of medicinal applications as it continues to progress.

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