Advancing Science and Technology through Multidisciplinary Innovation toward the Future

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PREFACE

The advancement of science and technology has always been a driving force in shaping societies, economies, and cultures across the globe. In the 21st century, this momentum has gained unprecedented speed, fueled by multidisciplinary research and innovation. The present volume, *Advancing Science and Technology through Multidisciplinary Innovation toward the Future*, is a testimony to the diverse, yet interconnected, fields of inquiry that are addressing contemporary challenges while envisioning a sustainable future.

This book brings together contributions from researchers, academicians, and practitioners across domains such as pharmacology, nanotechnology, biomedical engineering, artificial intelligence, material science, and literary studies. Each chapter reflects a unique perspective on innovation, rooted in its discipline yet extending beyond disciplinary boundaries to create synergies that are essential for holistic development. From drug discovery and biomedical devices to sustainable construction materials and advanced alloys, the research presented here demonstrates how science and technology can serve as a bridge between theoretical exploration and practical application.

What makes this volume distinctive is its conscious engagement with global goals—health and well-being, sustainability, inclusivity, and technological empowerment. By integrating modern approaches such as artificial intelligence in healthcare, green nanotechnology in material sciences, and ergonomic rehabilitation devices for enhanced quality of life, the book underscores the role of innovation as a catalyst for social transformation. Simultaneously, the literary explorations remind us that human values, cultural narratives, and

gender perspectives remain central in balancing technological progress with ethical and societal considerations. The collective effort represented here is not merely a compilation of research findings but an invitation to think across boundaries. It encourages readers to see science and technology not in isolation, but as part of an ecosystem where knowledge flows freely, challenges inspire creativity, and collaboration drives solutions.

We believe this book will serve as an inspiration for scholars, students, and professionals to further the dialogue between disciplines, to innovate responsibly, and to harness knowledge for building a future that is both technologically advanced and human-centered. We would like to extend our sincere thanks to our publisher, Scientific Research Reports, Chennai, India, for their dedicated efforts in preparing this book, which provides enriched content.

Wishes and Regards,

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Chapter 1

Genus Suaeda: Advances in Pharmacology and Clinical Applications Supporting SDG 3 – Good Health and Well-being

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Abstract

The genus Suaeda, comprising halophytic species native to saline and coastal ecosystems, has emerged as a promising source of pharmacologically active compounds with wide-ranging health benefits. Recent studies highlight the therapeutic potential of Suaeda maritima, S. salsa, and S. glauca in managing chronic conditions such as diabetes, hypertension, liver fibrosis, and inflammation. Bioactive constituents—including flavonoids, polyphenols, and ACE inhibitory peptides—present robust cytoprotective, antioxidant, and anti-inflammatory activity. These advances resonate strongly with the objectives of Sustainable Development Goal 3, which promotes universal access to effective medicines and healthcare technologies. Moreover, the sustainable cultivation of Suaeda in marginal soils supports resilient public health systems in vulnerable regions, bridging ecological sustainability with clinical relevance. This review

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underscores the genus's role as a natural ally in achieving global health equity through integrative, SDG-oriented research. More than 100 species of annual herb genus Suaeda widely distribute (Asia, North America, northern Africa and Europe), are rich in resources (about hundreds of millions of tons/Y) and have a long historical application. Most of them are mainly used for traditional food, feed and medicine. Recently, they have been employed to repair saline-alkali land and beautify the environment. So far, only 27 species have been reported on the bioactivity diversity, broad spectrum and effectiveness in clinical practice. Therefore, the in-depth and extensive research of Suaeda has become a research hotspot around the world. However, only one review summarized the nutritional, chemical and biological values of Suaeda. By searching the international authoritative databases (ACS Publications, ScienceDirect, PubMed, Springer, web of Science and Bing International etc.) and collecting 100 literatures closely related to Suaeda (1895–2024), herewith a comprehensive and systematic review was conducted on the phytology, chemistry, pharmacology and clinical application, enveloping the classification evolution between Amaranthaceae and Chenopodiaceae, distribution and common botanical characteristics; involving 9 chemical categories of 163 derivatives covering 14 new and 6 first-isolated ones, and appraising the content determination of 6 categories of components; mainly including the pharmacology of 13 species in vivo and vitro; estimating the clinical application of 16 species cured the related diseases of eight human physiological system except for the motor system. It is expected that this paper will provide forward-looking scientific ideas and literature support for the further modern research, development and utilization of the genus.

Keywords: Suaeda Vermiculata; medicinal uses; anticancer mechanism; hepatoprotective activity; Sustainable Development Goal 3 - Good Health and Well-being;

1. Introduction

Genus Suaeda, known as seablites or seepweeds, is an annual herbaceous succulent salt-accumulating plant in Chenopodiaceae. There are more than 100 species of it, the 27 species among them have been studied and reported presently, which are distributed all over the world and mainly grow on saline-alkali lands such as seashore and wasteland [1]. Genus Suaeda is often used as green food or livestock feed in its growing areas. S. maritima was used as food in the Basque region and the northern Netherlands in the late Neolithic. In the area near the Mediterranean and Europe, the seeds of S. vera, S. vermiculata, and S. fruticosa, S. moquinii, S. aralocaspica, S. salsa etc. can be regarded as alternative sources of high-quality edible oil, S. diffusa is often eaten during the Lenten season in Mexico it is also often selected as a seasoning in the United States. S. nudiflora can be sold as plant salt andprovided as nutraceuticals. In India and central Saudi Arabia, S. esteroa, S. vermiculata and S. maritima are employed as forage for cattle, camels, goats, and sheep. S. monoica was used in papermaking. Besides, In China, S. salsa can develop edible oil, make beverages, pasta and other products to drive the development of food industry in China [2].

In addition, Suaeda can repair saline-alkali land and protect the environment to promote the development of agriculture and tourism. Due to irrigation methods and industrial pollution, many parts were affected by salinization and heavy metal pollution, especially coastal, arid, and semi-arid areas around the world, it becomes a worldwide

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environmental problem. In recent years, the method of phytoremediation has attracted more and more attention because of its low cost, low invasiveness and high safety. Halophytes are the most suitable species to repair heavy metal polluted saline soil since their high tolerance to heavy metals. Suaeda can flourish in saline-alkali soil, and has a cumulative effect on common metals such as Cu, Zn, Pb, and Cd, and its contents are higher than the background value of the tidal flat.

It can monitor the content of Hg in the environment, quickly enrich cadmium metals in water and remove phenols. It can also effectively reduce the amount of soil surface salt, increase the content of soil organic matter and enhance the content of N, P, and K in soil. It can make more and more organic matter on the high salt tidal flat that is not completely separated from the seawater, and accelerate the soil transformation process of the tidal flat. S. monoica can remove 453.55 kg sodium chloride in the soil from one hectare land in four monthS, which can be used successfully to reclaim salt affected agricultural lands and rendering them more suitable for crop production after few repeated cultivation, which greatly promotes the development of agriculture. S. salsa is known as the "pioneer plant" of saline alkali land transformation because of its high salt tolerance. It can protect the vegetation of Momoge wetland and Panjin Wetland in China from saline alkali soil, provide living habitat and breeding ground for aquatic and terrestrial organisms, and maintain biological species diversity. Therefore, tourism is developed in local wetland parks, including the Ariake Sea in Japan, which has driven local economic development [3].

Figure. 1: Suaeda vermiculata

1.1 Characteristics [4]

Table 1: S.Vermiculata

Family	**Chenopodiaceae**
Classification	On the endangered species list
Ecosystem	Desert
Chorotype	Saharo-Arabian
Conservation Site	Evrona salt marsh

1.2 Common Names

- Vermiculata Suaeda
- Vermiculata's Suaeda
- Suaeda Vermiculata

1.3 Synonyms

- Lerchia fruticosa (Forssk. ex J.F.Gmel.) Medik.
- Salsola mollis Desf.
- Suaeda fruticosa Forssk. ex J.F.Gmel.
- Suaeda mesopotamica Eig
- Suaeda mollis (Desf.) Delil

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- Schoberia fruticosa (Forssk. ex J.F.Gmel.) C.A.Mey.
- Chenopodium alexandrinum Desf. ex Moq.
- Dondia fruticosa (Forssk. ex J.F.Gmel.) Druce

1.4 Description [5]

Suaeda vermiculata is a species of plant in the family Amaranthaceae (formerly classified under the Chenopodiaceae).It is a salt-tolerant plant (halophyte) that grows naturally in salt-affected areas. It is a shrub and can grow to 0.4–1 m height, with woody stems at its base, very branched. Its distribution includes Africa and the Middle East, including North Africa, the Arabian Peninsula, Yemen's Socotra, Iraq, Jordan and Palestine to the east of India as well as the Canary Islands in Cape Verde and from Senegal, Mauritania and Mali to Chad, Sudan, South Sudan, Kenya, Ethiopia and Somalia. They are found in coastal bushlands as well as inland saline sites, sand plains, stony places and desert wadis between sea level and 400 meters in altitude [2]. It also occurs in dry riverbeds and other saline locations in southern Africa in association with Tamarix usneoides and the grass Odyssea paucinervis.

Grows in extreme desert salt marshes ("Ka") in whose center there is saline clay soil, as well as in humid salt marshes in warm deserts.

Figure 2: S. Vermiculata plant

1.5 Cultivation and Propagation

Suaeda vermiculata is a perennial shrub that is native to the Mediterranean region. It is tolerant of drought and salt and grows best in full sun. Propagation is by seed or cuttings. Seeds should be sown in spring or early summer in well-drained soil. Cuttings should be taken in late summer or early autumn and planted in a sandy soil mix.

1.6 Adaptations to salinity and drought [6]

Figure 3: S.Vermiculata with fruit and flower

Plants have developed several tolerance mechanisms that improve their ability to reach suitable habitats and have adapted several features that allow them to function in a changing local environment. S. vermiculata adapts various structural characteristics and modifications to cope with salinity and drought stresses. These adaptive features include succulence, leaf burns, shedding of leaves, stunted growth habit and change in the colour of the leaves (Fig. 1), thick cuticular layers and sunken stomata.

1.7 Different colours and shades of S.Vermiculata

Suaeda is a genus of plants also known as seepweeds and sea-blites. Most species are confined to saline or alkaline soil habitats, such as coastal salt-flats and tidal wetlands. Many species have thick, succulent leaves, a characteristic seen in various plant genera that

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thrive in salty habitats (halophile plants).

There are about 110 species in the genus Suaeda.

The most common species in northwestern Europe is S. maritima. It grows along the coasts, especially in saltmarsh areas, and is known in Britain as "common sea-blite", but as "herbaceous seepweed" in the USA. It is also common along the east coast of North America from Virginia northward. One of its varieties is common in tropical Asia on the land-side edge of mangrove tidal swamps. Another variety of this polymorphic species is common in tidal zones all around Australia (Suaeda maritima var. australis is also classed as S. australis). On the coasts of the Mediterranean Sea a common Suaeda species is S. vera. This is known as "shrubby sea-blite" in English. It grows taller and forms a bush.

The name Suaeda comes from an oral (non-literary) Arabic name for the Suaeda vera species transliterated as suaed, sawād or suēd,and it was assigned as the genus name by the 18th century taxonomist Peter Forsskål during his visit to the Red Sea area in the early 1760s. Forsskål's book, Flora Aegyptiaco-Arabica, published 1775, in Latin, declares Suæda as a newly created genus name, with the name taken from an Arabic name Suæd and presents the species members of the new genus.

The genus includes plants using either C3 or C4 carbon fixation. The latter pathway evolved independently three times in the genus and is now used by around 40 species. S. aralocaspica, classified in its own section Borszczowia, uses a particular type of C4 photosynthesis without the typical "Kranz" leaf anatomy [7].

Figure 4: Different shades of S.Vermiculata

2. Suaeda vermiculata

It is a halophytic member of the family Chenopodiaceae, which grows naturally in the Egyptian coastal region. Some earlier works concerned with prophylactic characteristic of wild plants showed that S. vermiculata has high quantities of phenolics and flavonoids with a pronounced antioxidant activity. Additionally, S. vermiculata has been demonstrated to have hypoglycemic, hypolipidemic, and antitumor activities. Such activities were attributed to polyphenolic compounds (including flavonoids) in the aerial parts of the plant. Nevertheless, triterpenoids and polyphenols in S. vermiculata increased the pharmacological importance of the plant due to its role in preventing cardiovascular and cancer diseases [8].

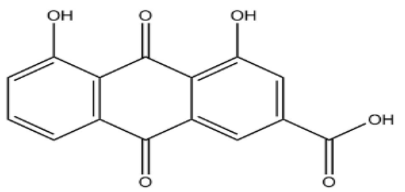

Figure 5: Rhein, Rhenic acid

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2.1 Pharmacological Properties [9]

- Suaeda plants have been found to possess various biological activities, including antioxidant and anti-inflammatory properties.

- Studies have identified compounds like 3-epi-lupeol and 4-cyclopentylpyrocatechol with potential medicinal applications [1].

2.2 Clinical Applications

- Research has explored the potential of Suaeda plants in treating various health conditions, including those related to stress tolerance and environmental pollution.

- The genus Suaeda has been studied for its role in saline soil reclamation and biofuel production, which can indirectly contribute to improved health and well-being by promoting sustainable development.

2.3 Supporting SDG 3: Good Health and Well-being

- By developing new medicines and treatments from Suaeda plants, we can work towards reducing mortality rates and improving health outcomes, aligning with SDG 3's targets.

- Additionally, Suaeda's potential in environmental remediation can help reduce pollution-related illnesses and deaths, further supporting SDG 3's objectives.

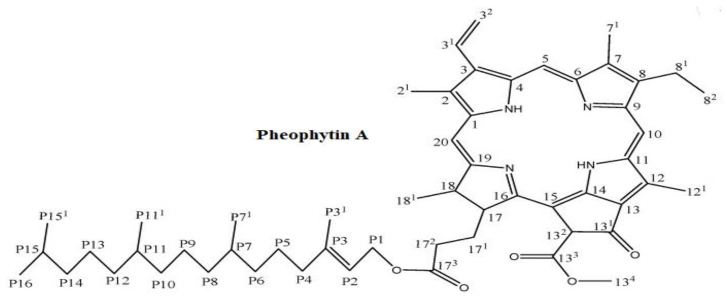

Figure 6: Pheophytin A

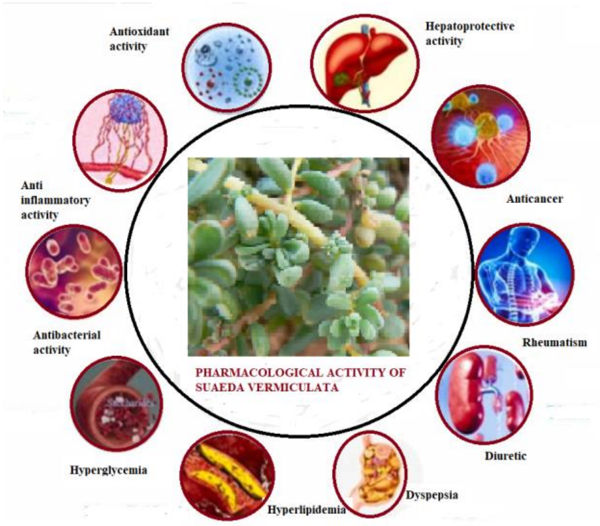

Figure 7: Proposed pharmacological activity of S.Vermiculata

2.4 Proposed mechanism of anticancer activity

Proposed mechanisms involved in in vitro anticancer activity of surfactin. The anticancer activity of Rhein is associated with growth inhibition, cell cycle arrest, cell death (apoptosis), and metastasis inhibition. Surfactin treatment can inhibit cancer cell viability by inactivating the cell survival signaling pathways. Besides, surfactin regulates cell cycle-regulatory proteins, which are pivotal for cell cycle phase transition to block the proliferation of cancer cells. The apoptotic effect (intrinsic mitochondrial/caspase pathway) of surfactin is mediated by two different pathways that are triggered by high intracellular ROS formation, namely ERS/[Ca 2+] /ERK1/2 and JNK/m /[Ca 2+] /Bax-to-Bcl-2 ratio/cyt c pathways. Surfactin-induced apoptosis is also associated with the changes in phospholipids composition that leads to a significant decrease in unsaturated degree of cellular fatty acids. Apart from these, surfactin also inhibits the invasion, migration and colony formation of cancer cells in the virtue of MMP-9 expression change that involves the inactivation of NF-κB, AP-1, PI3K/Akt, and ERK1/2 signaling

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pathways [10].

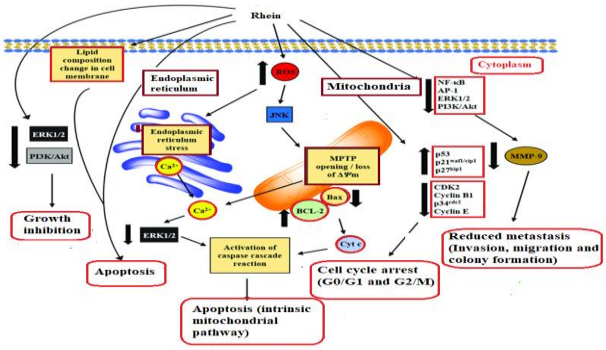

Figure 8: Anticancer mechanism of S.Vermiculata

2.5 Pharmacological mechanisms of rhein on DM Insulin resistance

Insulin resistance (IR) is a common risk factor for various endocrine, metabolic, and cardiovascular diseases. Similarly, rhein can play a role in reducing IR, thereby inhibiting DM progression. Insulin resistance prevents insulin from performing its normal physiological function, causing high blood glucose. This results in hyper insulinism and a series of changes such as hyperglycemia and obesity. Rhein significantly improves glucose tolerance without regulating insulin secretion in streptozotocin (STZ)-induced diabetic mice.

The hexosamine pathway (HBP) is an intracellular glucose metabolism pathway. Under normal circumstances, only 1%–3% of glucose enters the HBP. Specifically, after rhein stimulation, the activity of glutamine fructose-6-phosphate aminotransferase (GFAT) in the first step of the HBP decreases, and the formation of UDP-N-acetyl glucosamine, the final product of HBP, decreases significantly. Glucose transporter 1 (GLUT1) is the key glucose transporter in mesangial cells and is responsible for their basal metabolism; its expression level is often the main rate-limiting step in cellular glucose metabolism. Modern research has found that rhein can significantly reduce the glucose uptake rate of mesangial cells were transduced with the human GLUT1 gene (MCGT1) in a dose-dependent manner. In mesangial cells, transforming growth factor-β (TGF-β1) stimulates extracellular matrix (ECM) synthesis and cell hypertrophy as a result of high glucose concentrations. Rhein inhibits the upregulation of plasminogen activator inhibitor-1 (PAI-1) mRNA expression in TGF-β1-induced endothelial cells in a dose-dependent manner and the production of endothelial PAI-1 protein and has a significant inhibitory effect on the activity of phosphor-p44/p42 mitogen-activated protein kinase (MAPK) induced by TGF-β1 in human endothelial cells. Rhein is transmitted through protein kinase C (PKC), and MAPK inhibits the abnormal increase in GLUT1 mRNA expression, thereby antagonizing the pathological effects of TGF-β1 on mesangial cells. GFAT is the key enzyme in HBP, and its activity intensity reflects the active state of HBP. Liu Q. found that rhein inhibits the activity and expression of GFAT in the skeletal muscle of IR mice, 3T3 L1 adipocytes, and C2C12 myoblast models of IR induced by high glucose and insulin levels, thereby inhibiting HBP flow and down regulating the glycosylation modification level of the protein O-linked N-acetyl glucosamine. [11].

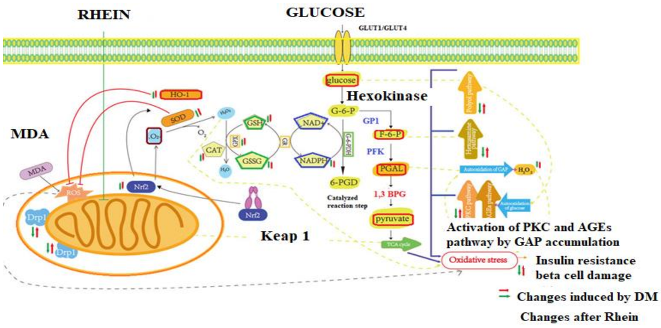

Figure 9: Anti diabetic activity

2.6 Hepatoprotective activity

Halophytic plants, growing under high-salinity soil conditions, have

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also been recorded to provide relief from symptomatic liver discomforts. The halophytes, under the stress of harsh super-saline habitats in areas with the lowest rainfall and marshy conditions, as well as desert environments, have accustomed to adverse environmental conditions through developing various defense mechanisms for survival. These adoptive techniques include multiple strategies which are morphological, biochemical, physiological, metabolic, and sensory in nature. One such strategy of these halophytes is their responsiveness to elevated oxidative stress conditions of the plants, wherein these plants survive high-salinity conditions by producing specific enzymatic, non-enzymatic, and metabolite products, many of which are secondary metabolite antioxidant molecules concentrated abundantly in the plant sap. These products have well-established roles in quenching reactive oxygen species (ROS). The observation that halophytes are rich in antioxidant constituents lends credence to the hepatoprotective claims regarding this category of the plants. The oxidative stress is implicated in the pathogenesis of various other diseases, including liver disorders [12].

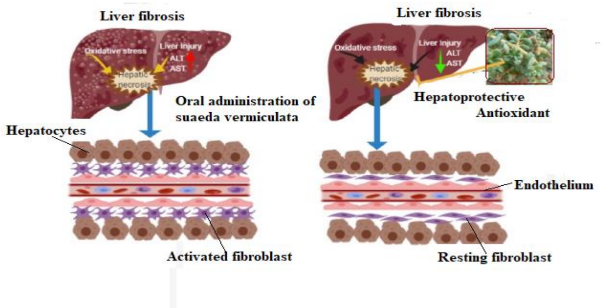

Figure 10: Hepatoprotective activity

3. Conclusion

Gallic acid and its derivatives demonstrated management of several disorders, also their acceptable options to be introduced as dietary supplements Studies presented here showed that the most important pharmacological properties of gallic acid potentials. In addition, gallic acid is involved in various signaling pathways that regulate the wide range of pathways, NO signaling pathway, intrinsic and pathway. S.Vermiculata are attributed to its antioxidant, anticancer, hepatoprotective, anti-diabetic and anti-inflammatory potentials. In addition, S.Vermiculata is involved in various signaling pathways that regulate the wide range of biological functions including pro- and inflammatory pathways, NO signaling pathway, intrinsic and extrinsic pathways of apoptosis, and NF-κB signaling pathway. S.Vermiculata and its derivatives demonstrated a broad range of beneficial effects in prevention and/or management of several disorders, also their acceptable safety and stability profiles, make them significant options to be introduced as dietary supplements. Sustainable Development Goal 3, which promotes universal access to effective medicines and healthcare technologies.

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Chapter 2

Green Synthesis of Selenium Nanoparticles using leaf extract of Mukia maderasapatana and deciphering its biomedicinal properties

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Abstract

Selenium nanoparticles (SeNPs) are tiny particulates, which possess the ability for assimilation by biological systems, and have garnered attraction among researchers due to its exceptional biological properties and potential therapeutic functionalities. In the present study, SeNPs were synthesized via an effective and eco-friendly technique using leaf extract of Mukia maderaspatana. Then SeNPs were characterized by various analytical techniques. UV-Vis spectroscopy showed absorption peak at 265 nm. Biomolecules acts as stabilizers for synthesized SeNPs. Alcoholic group, nitro compounds, aromatic compounds in SeNPs is revealed by the O-H bond, N-O bond and C-C bond by FTIR analysis. SEM analysis showed dimensions of synthesized SeNPs ranging from 73.24 nm to 187.6 nm. EDX analysis highlights the elemental composition of SeNPs as (13.75%) of Selenium, (69.27%) of oxygen and (16.98%) of sodium, and XRD spectroscopy revealed the crystalline structure of SeNPs. The antioxidant potential of SeNPs via in vitro assays like NO,

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ABTS, FRAP and H2O2 showed higher inhibition as 86.71%, 89.18%, 87.54%, and 89.9% at a concentration of 50 µg/ml. Antiinflammatory effects of SeNPs demonstrated a noteworthy inhibition of Bovine Serum Albumin, Egg Albumin denaturation as 78% and 77%, also in membrane stabilization with increase in the concentrations of SeNPs it stabilizes the cellular membranes. Brine shrimp lethality assay performed to assess the cytotoxicity effects of SeNPs and recorded the 50% of survival at 80 µg/mL of concentration, and thereby validated its biosafety profile and potential therapeutic index. Collectively, this investigation highlights the multifunctional capabilities of SeNPs as promising candidates for applications in the biomedical field.

Keywords: Selenium nanoparticles; Mukia maderaspatana; green synthesis; antioxidant; anti-inflammatory; Cytotoxicity

1. Introduction

In recent years, nanotechnology has emerged as an innovative discipline with multifaceted applications across a spectrum of scientific fields, notably in the medicine domain [1]. Nanoparticles are defined as particles that exhibit dimensions in the range of 10^-9 meters, and those nanoparticles formed from metallic elements are referred to as metallic nanoparticles. These nanoparticles exhibit a wide variety of applications in diverse domains, such as biotechnology, medicine, cosmetics and others. It also possesses numerous beneficial properties relevant to health and diagnosis. Due to their distinctive characteristics and properties that are dependent upon their size, metallic nanoparticles have garnered substantial focus from scientists [2]. The synthesis of nanoparticles via the utilization of plant sources or their derivatives is known as green synthesis, and this method is recognized for its safety, economic feasibility, and environmental sustainability. It dispenses the obligation for toxic chemicals or reducing agents; instead the extract of plant serves as a reducing agent. The plant extract promotes the metal ion reduction; leading to the nanoparticle formation. Nanoparticles synthesized via sustainable eco-friendly methodologies exhibits a diverse range of beneficial properties, including antioxidant, antimicrobial and antitumor activities [3]. Selenium (Se) is categorized as a metalloid, manifesting features to both metals and non-metals. It has been confirmed that selenium serves as an integral dietary micronutrient vital for the optimal physiological efficacy of the human body. It includes a diverse collection of important medical applications [2]. Previous studies have revealed that selenium plays an essential function in the diverse disease prevention, including cystic fibrosis, cardiovascular disorders, and stress-related conditions [4].

In biological systems, selenium is an essential trace element, exhibiting specific functions in numerous health-related processes. In various allotropic forms selenium exhibits which includes both amorphous and crystalline configurations, and It is considered as a remarkable material due to its chemical versatility for the synthesis of nanoparticles [1]. Selenium nanoparticles (SeNPs) exhibits enhanced bioactivity and lower in toxicity in contrast to various sources of selenium such as selenate and selenomethionine. Recently, SeNPs have drawn significant academic attention as a vital research area due to their tiny size and remarkable physical and chemical properties, with an enhanced focus on their synthesis methods, features,and potential uses in the life sciences stream [5]. Hence, the green synthesis of SeNPs has garnered considerable interests of the researchers about their potential uses in the

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biomedical field. The biosynthetic process for SeNPs is recognized for its safe, non-toxic and environmentally friendly aspects. Moreover, owing to the organic compounds residing on their surfaces biosynthesized SeNPs shown greater stability which effectively deter the nanoparticles aggregation over time [6].

Oxidative stress refers to the presence of entities known as free radicals and reactive oxygen species (ROS), which are generated during standard physiological processes but can become harmful when not adequately neutralized by endogenous defense mechanisms. Indeed, oxidative stress arises from a dysregulation between the production of reactive oxygen species and the capacity of endogenous antioxidant systems to mitigate their effects. ROS serve as principal agents that trigger oxidation and induce oxidative stress, which is implicated in a myriad of diseases and pathological conditions. An excessive accumulation of ROS is detrimental, as it instigates biomolecular oxidation that culminates in cellular apoptosis and the manifestation of oxidative stress. Furthermore, oxidative stress incites inadvertent activation of enzymes and leads to oxidative damage within the cellular environment [7].

This ROS facilitates the oxidative impairment of macromolecules, leading to the onset of various diseases. Human possesses an intrinsic protective mechanism designed to inhibit the generation of free radicals. These protective systems may be compromised under certain pathological states, necessitating the introduction of antioxidant supplements to stave off the production of free radicals. Antioxidants engage with the oxidation process via radical scavenging and chelating activities, thereby mitigating the oxidative damage instigated by free radicals. A variety of synthetic compounds, including butylated hydroxylanisole and butylated hydroxyltoluene, are commercially accessible; however, these compounds are associated with numerous adverse effects in both humans and animals. Conversely, plant-derived constituents such as flavonoids, tannins, proanthocyanidins, and phenolic compounds exhibit robust antioxidant properties [8].

Inflammation constitutes a cellular and tissue response to injury triggered by a multitude of factors, including infectious agents, chemical substances, thermal exposure, and mechanical trauma [9]. The management of inflammation predominantly involves the utilization of both steroidal and nonsteroidal anti-inflammatory pharmacological agents. Within the domain of biomedicine, especially concerning anti-inflammatory therapies, the integration of nanotechnology has been extensively explored and thoroughly established [10]. A significant proportion of anti-inflammatory pharmaceuticals function as potential inhibitors of the cyclooxygenase (COX) pathway, which is integral to the metabolism of arachidonic acid, subsequently leading to the synthesis of prostaglandins, acknowledged as the key mediators of the inflammatory process. The suppression of prostaglandin biosynthesis is critical for the effective management of inflammation. Consequently, the administration of analgesic and anti-inflammatory compounds is deemed necessary for therapeutic intervention. The presently accessible anti-inflammatory pharmacological agents pose significant hazards to human health, particularly in terms of their toxicity and the probability of relapse of the disorder after the discontinuation of treatment. The traditional system of plant-based medicine plays a crucial role in healthcare, with numerous plant extracts and their isolated constituents recognized as potent anti-inflammatory agents [9]. Recently, the utilization of medicinal plants

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has been investigated to formulate nanoparticles (NPs), aimed at enhancing therapeutic efficacy while mitigating adverse effects [10].One of the most extensive and heterogenous groups of flora, comprising both domesticated and wild species is Cucurbitaceae family. The species belonging to this family are generally regarded as "Cucurbits" and are valued for their significant contributions of vital dietary macromolecules. Furthermore, it is extensively used in Ayurvedic systems and in modern medical practices to solve a multitude of health-related issues [11].

Mukia maderaspatana is commonly referred as Madras pea pumpkin, a medicinal species generally found in tropical and subtropical zones [12]. Leaves are generally utilized for various applications among the different parts of the plant. Within the Indian cultural milieu, traditional practitioners employ various plant materials in several forms such as decoctions, extracts, juices and salads to tackle a wide range of health challenges [13]. Nonetheless, existing literature regarding the antioxidant and cytotoxic properties of M. maderaspatana remains notably sparse. Taking into account the previously highlighted insights and reinforced by the scientific corpus, the current research marks the pioneering systematic investigation into the cytotoxic potential of selenium nanoparticles synthesized from M. maderaspatana, alongside a comprehensive exploration of its antioxidant and anti-inflammatory activities.

Table 1: Elemental composition of synthesized SeNPs

Element Line	**Weight %**	**Weight Error %**	**Atom %**
O K	42.88	± 1.33	69.27
Na K	15.10	± 0.90	16.98
Se K	Nil	Nil	Nil
Se L	42.02	± 1.26	13.75
Total	100.00		100.00

2. Figures

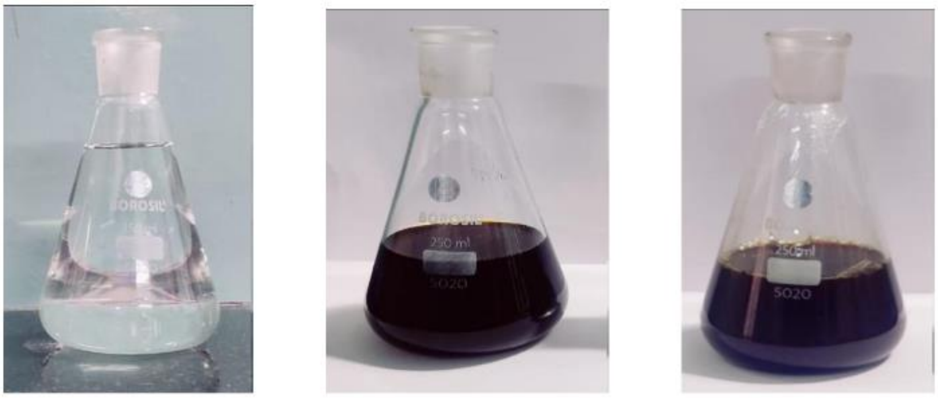

Figure. 1: Biosynthesis of Selenium Nanoparticles. a.Sodium selenite, b.*Mukia maderaspatana* extract, c. SeNPs formed

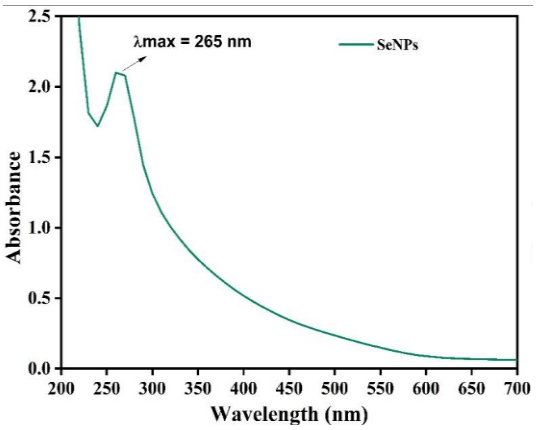

Figure. 2: UV-visible spectrum of SeNPs

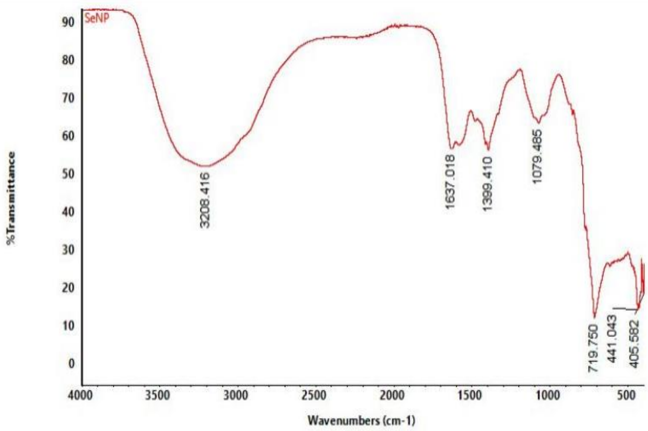

Figure. 3: FT-IR spectrum of SeNPs

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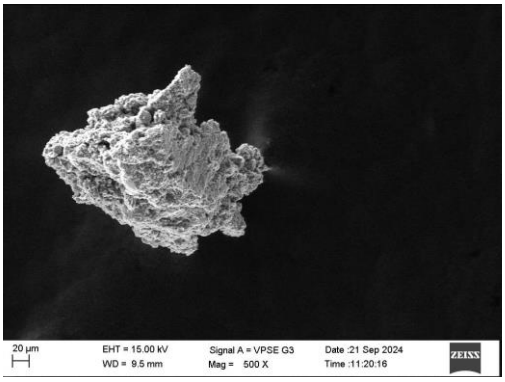

Fig.4. SEM analysis of SeNPs

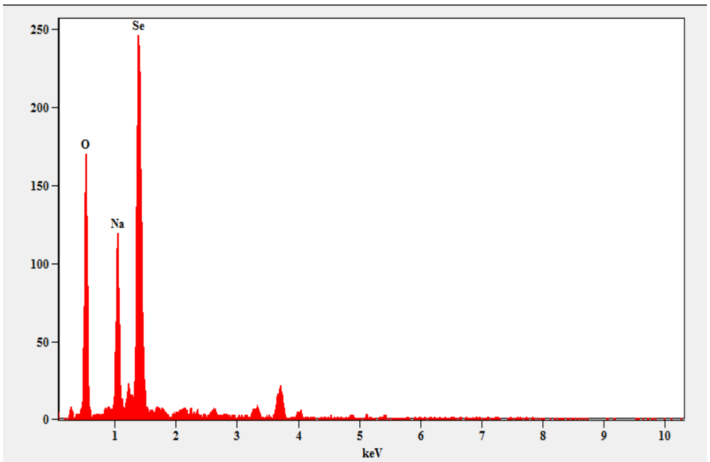

Fig.5. EDX spectrum of SeNPs

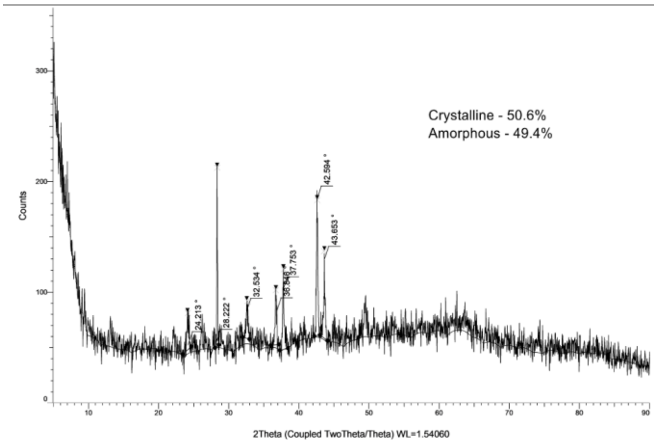

Fig. 6. XRD pattern of SeNPs

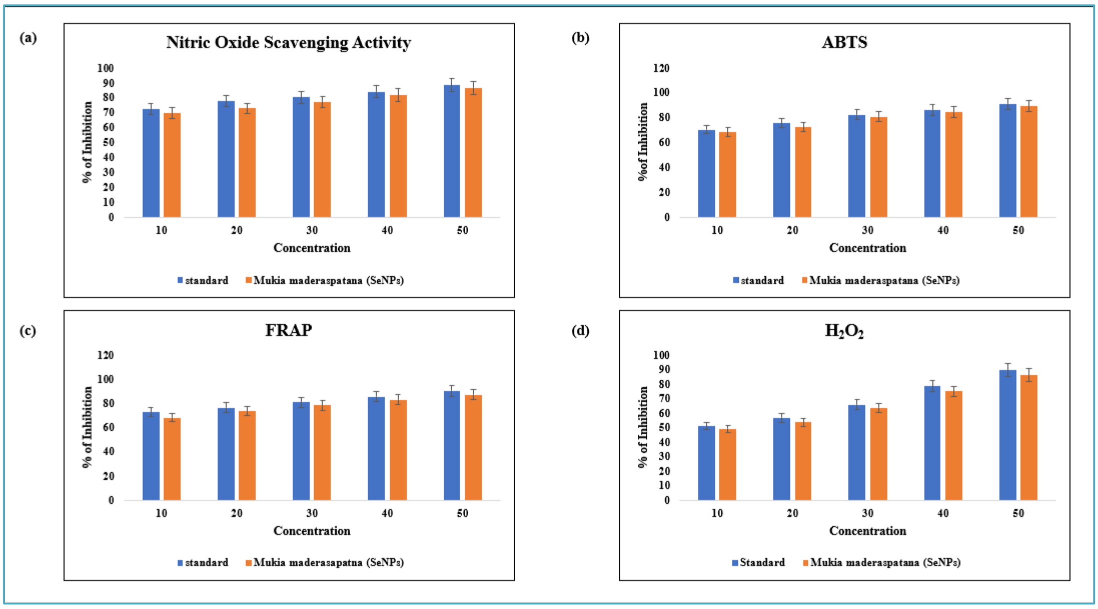

Fig. 7. In vitro Antioxidant assays – (a) Nitric Oxide Scavenging Activity, (b) ABTS scavenging activity, (c) Ferric reducing antioxidant power assay, (d) Hydrogen peroxide scavenging activity

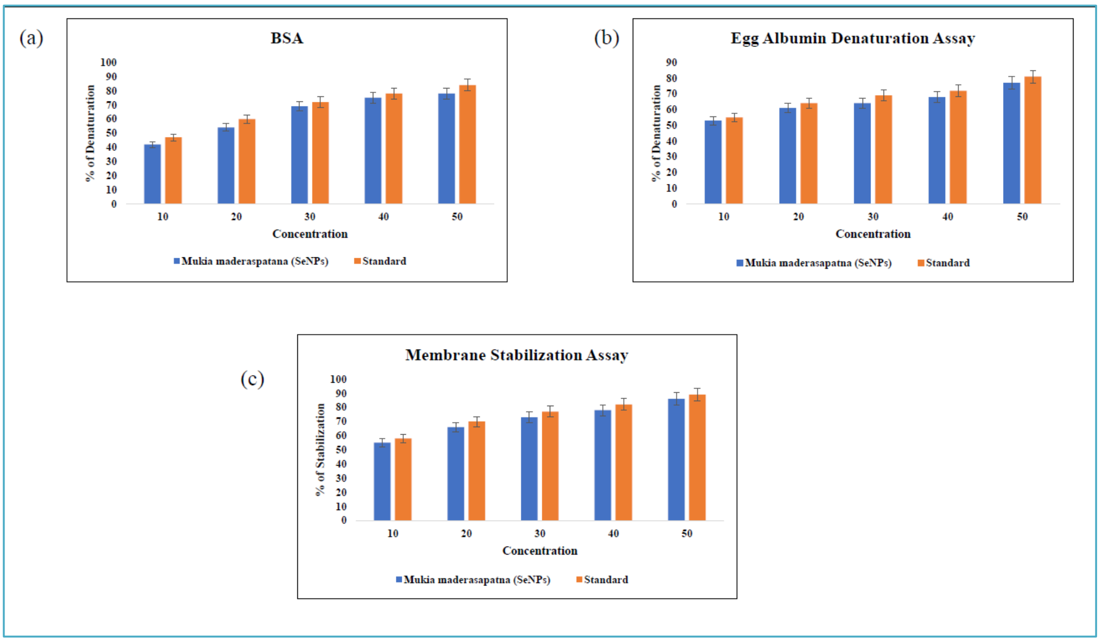

Fig.8. In vitro Anti-inflammatory assays – (a) Bovine Serum Albumin (BSA) Denaturation Assay, (b) Egg Albumin Denaturation Assay, (c) Membrane Stabilization Assay

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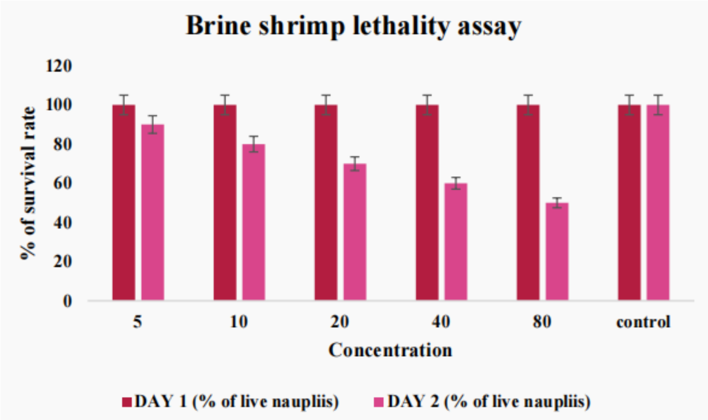

Fig. 9. Brine shrimp lethality assay

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Chapter 3

Self-Micro Emulsifying Drug Delivery Systems (SMEDDS) for Phytopharmaceuticals

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Abstract

Phyto-pharmaceuticals have gained increasing attention due to their therapeutic potential and natural origin. However, their clinical utility is often compromised by poor aqueous solubility, low permeability, chemical instability in the gastrointestinal tract, and extensive first-pass metabolism, leading to poor oral bioavailability. Self-Micro-emulsifying Drug Delivery Systems (SMEDDS) have emerged as a promising lipid-based delivery approach to overcome these challenges. SMEDDS are isotropic mixtures of oils, surfactants, and co-surfactants that spontaneously form fine oil-in-water micro-emulsions upon mild agitation in gastrointestinal fluids. These systems significantly enhance drug solubilization, protect labile constituents, and improve intestinal absorption and lymphatic transport. This chapter provides a comprehensive overview of the formulation, characterization, and evaluation of SMEDDS, with special emphasis on their application in enhancing the bioavailability of key herbal drugs such as curcumin, silymarin, boswellic acids, and quercetin. Moreover, the chapter explores existing hurdles, regulatory

considerations, and the evolving clinical potential of SMEDDS in the advancement of phyto-pharmaceutical drug delivery.

Keywords: Phytop-harmaceuticals; Lipid-based systems; Nanoemulsion; Bioavailability enhancement; Drug solubilization; Lymphatic transport;

1. Introduction

Herbal medicines have formed the basis of health care throughout human history. Even today, a significant portion of the global population relies on plant-derived remedies for primary health care. Despite their widespread usage and therapeutic potential, herbal drugs often face a significant challenge: poor bioavailability. The extent of bioavailability is primarily determined by the compound's dissolution characteristics, its ability to traverse biological membranes, and its resilience against degradation within the gastrointestinal tract .Many phytochemicals are lipophilic, poorly soluble in water, and susceptible to degradation in acidic environments or by enzymatic activity. Consequently, their therapeutic efficacy is reduced when administered orally.

This presents a compelling case for the development of advanced drug delivery systems aimed at enhancing the pharmacokinetic profile of phyto-pharmaceuticals. Common herbal compounds affected by poor bioavailability include curcumin (from Curcuma longa), resveratrol (from grapes), silymarin (from milk thistle), and boswellic acids (from Boswellia serrata).

2. Importance of Bioavailability

Bioavailability refers to the rate and extent to which the active ingredient or active moiety of a drug is absorbed and becomes available at the site of action. For orally administered drugs, this

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depends on dissolution in gastrointestinal fluids, absorption through intestinal walls, and metabolic stability. Many herbal drugs demonstrate poor aqueous solubility and are substrates for efflux transporters like P-glycoprotein or metabolizing enzymes like CYP3A4, resulting in minimal systemic availability.

Improving bioavailability can significantly enhance therapeutic outcomes, reduce dosing frequency, and minimize side effects. Innovative formulation strategies—including micronization, solid dispersion technologies, nanoemulsion systems, and lipid-based carriers such as Self-Microemulsifying Drug Delivery Systems (SMEDDS)—are actively under investigation to enhance the bioavailability of poorly soluble compounds.

3. Need for Advanced Drug Delivery in Herbal Medicines

The pharmaceutical industry is shifting from conventional dosage forms to advanced delivery systems to improve therapeutic outcomes. For herbal drugs, novel delivery systems are essential not only to enhance bioavailability but also to overcome issues of stability, dosage accuracy, and patient compliance.Among various systems explored, Self-Microemulsifying Drug Delivery Systems (SMEDDS) have emerged as promising carriers due to their ability to solubilize lipophilic drugs and promote lymphatic transport. SMEDDS bypass first-pass metabolism and improve absorption via mucosal membranes, making them suitable for delivering phytoconstituents.

4. Self-Micro emulsifying Drug Delivery System [SMEDDS]

Self-Microemulsifying Drug Delivery Systems (SMEDDS) are isotropic mixtures of oil, surfactant, and co-surfactant that spontaneously form oil-in-water microemulsions upon mild agitation in gastrointestinal fluids. They contain droplet sizes typically below 100 nm, offering a large interfacial surface area that facilitates rapid dissolution and absorption. Unlike classical emulsions, SMEDDS undergo self-emulsification without mechanical agitation and maintain their structural integrity due to inherent thermodynamic stability. The ability to encapsulate poorly water-soluble herbal drugs and enhance permeability makes SMEDDS an attractive choice for phytopharmaceutical formulation development.

5. Components of SMEDDS

The development of a SMEDDS formulation requires meticulous identification and fine-tuning of its fundamental components:

Oil Phase: Serves as a solubilizing agent for lipophilic drugs. Representative lipid-based carriers often include medium-chain triglycerides, unsaturated fatty acids like oleic acid, and ester derivatives such as ethyl oleate.

Surfactants: Aid in reducing interfacial tension and facilitate microemulsion formation. Non-ionic surfactants like Tween 80, Cremophor EL, and Labrasol are commonly used.

Co-surfactants: Help in achieving the desired flexibility of the interfacial film, enabling formation of microemulsion. Transcutol P and PEG 400 are widely favored as auxiliary solubilizers in SMEDDS formulations.

6. SMEDDS Improves Herbal Drug Bioavailability

SMEDDS contribute to improved bioavailability through multiple functional advantages, including: Increased solubilization: Lipophilic phytoconstituents dissolve in the oil phase, maintaining them in a solubilized form. Protection from degradation: The lipidic encapsulation in SMEDDS acts as a physical and chemical barrier,

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mitigating the exposure of phytoconstituents to gastric acidity and enzymatic hydrolysis within the gastrointestinal tract. Enhanced absorption: The nano-sized droplets increase surface area and promote efficient intestinal uptake. Lymphatic transport: Lipid-based systems may bypass hepatic metabolism by entering lymphatic circulation. Rapid onset of action: Swift self-emulsification in gastrointestinal fluids expedites the dissolution and uptake of the drug, thereby enabling an earlier onset of its therapeutic response.

7. Case Studies of Herbal Drugs with SMEDDS

Several herbal bioactives have been successfully formulated into SMEDDS, resulting in significant improvement in pharmacokinetics and therapeutic efficacy: Curcumin; Poorly soluble in water, curcumin shows enhanced anti-inflammatory and anti-cancer activity when formulated in SMEDDS. Boswellic Acids; Used for osteoarthritis and inflammatory bowel disease, their SMEDDS formulations increase oral bioavailability. Silymarin; A Hepatoprotective flavonolignan from milk thistle, silymarin's bioavailability improved markedly with SMEDDS. Quercetin; A dietary flavonoid known for antioxidant and cardioprotective effects, quercetin’s permeability and stability are enhanced through SMEDDS.

8. SMEDDS contribute to improved bioavailability through multiple functional advantages, including

Thermodynamically stable formulation with spontaneous emulsification. Simplified Production and Commercial Scalability: The formulation's adaptability to conventional encapsulation methods—such as soft and hard gelatin capsules—enables efficient scale-up and industrial manufacturing without necessitating complex processing techniques. Dose reduction is possible due to improved bioavailability. Potential for improved patient compliance due to better efficacy and reduced side effects. Improved stability during storage as compared to aqueous formulations.

9. Limitations and Challenges

- Not suitable for hydrophilic drugs or herbal extracts with polar constituents.
- Potential toxicity of surfactants and solvents requires safety assessment.
- Regulatory hurdles in herbal formulation standardization and validation.
- Expensive screening and optimization process including the need for ternary phase diagrams.
- Difficulty in predicting in vivo behavior from in vitro performance due to variability in gastrointestinal physiology.

10. Evaluation of SMEDDS Formulations

Evaluation of SMEDDS includes multiple in vitro and in vivo studies to ensure their stability, efficacy, and reproducibility.

Key evaluation parameters include:

- Droplet size and Polydispersity Index (PDI): Measured using dynamic light scattering (DLS). Ideally, droplet size should be <100 nm for enhanced absorption.
- Zeta potential: Indicates surface charge and predicts physical stability of the formulation.
- Emulsification time: Time taken to emulsify upon dilution; shorter times are preferred.

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- Thermodynamic stability: Evaluated via heating-cooling cycles, centrifugation, and freeze-thaw cycles.
- Drug content and uniformity: Essential to ensure dose accuracy.
- In vitro drug release: Studied using dialysis membrane and simulated intestinal fluid.
- In vivo pharmacokinetic studies: Provide bioavailability data and therapeutic correlation.

11. Optimization Strategies for SMEDDS

Optimization of SMEDDS involves a systematic approach to determine the ideal composition using experimental design methods.

Common approaches include:

- Ternary phase diagrams: Help identify self-emulsifying regions using various oil-surfactant-co-surfactant combinations.
- Response Surface Methodology (RSM): Statistical method for analyzing effects of multiple formulation factors.
- Box-Behnken and Central Composite Design: Used for optimizing multiple variables such as droplet size, emulsification time, and drug loading.
- Design of Experiments (DoE): Ensures robust product development and batch-to-batch consistency.
- Optimization is critical to ensure efficacy, safety, and scalability.
- Regulatory Considerations in Herbal SMEDDS
- Formulating herbal medicines in advanced delivery systems such as SMEDDS brings regulatory challenges. Key considerations include:
- Standardization of herbal extracts: Due to batch variability in phytoconstituents.

- Toxicological evaluation of excipients: Surfactants and co-surfactants must be GRAS-approved.
- Compliance with pharmacopeial standards: Assay, stability, dissolution.
- Clinical trials: Safety and efficacy validation in human subjects.
- Patentability and intellectual property: Innovative SMEDDS formulations can be protected under patent laws.
- Global agencies such as WHO, EMA, and CDSCO are evolving regulatory frameworks to accommodate novel herbal delivery systems.

12. Future Perspectives and Clinical Potential

SMEDDS has significant potential in clinical practice for phytopharmaceutical delivery. Ongoing and future advancements include:

SMEDDS for co-delivery: Combining two or more bioactives with synergistic effects.

Targeted SMEDDS: Ligand-functionalized formulations for tissue-specific delivery.

Pediatric and geriatric formulations: Improved palatability and dose flexibility.

Commercialization: Several SMEDDS-based herbal products are under clinical trials.

Personalized medicine: SMEDDS formulations tailored to individual pharmacogenomics profiles.

13. Conclusion and Future Scope

With the growing interest in herbal medicines globally, SMEDDS can be instrumental in bringing standardized, efficacious, and patient-

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friendly formulations to the market. It addresses a major bottleneck in herbal drug delivery; poor bioavailability and provides a scientifically sound approach to improving therapeutic efficacy. Future research should focus on in vivo-in vitro correlation, clinical validation, and regulatory harmonization to make SMEDDS a mainstream strategy in herbal drug delivery.

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Chapter 4

Drug Repurposing: A Modern Approach to Drug Discovery

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Abstract

Drug repurposing, also known as drug repositioning, involves identifying new therapeutic uses for existing drugs. This approach offers a faster, safer, and more cost-effective alternative to traditional drug discovery, which is often time-consuming and expensive. Since repurposed drugs have already been tested for safety and pharmacokinetics, they can be rapidly advanced into clinical trials. Several well-known drugs, such as aspirin, sildenafil, and thalidomide, have successfully been repurposed for new indications. Repurposing can be done using experimental methods or computer-based technologies, including artificial intelligence and large drug databases. The COVID-19 pandemic highlighted the importance of drug repurposing in emergencies, with drugs like Remdesivir and Dexamethasone playing crucial roles. Despite its advantages, challenges such as limited profitability, and the need for further testing remain. With growing access to biomedical data and advanced computational tools, drug repurposing is poised to become a key strategy in modern medicine.

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Keywords: Medicine repurposing; Computational medicine discovery; Artificial intelligence; COVID- 19; Cost-effective treatment; individualized drug;

1. Introduction

Drug repurposing, or repositioning, is the process of finding new therapeutic uses for existing drugs. Unlike traditional drug discovery, which is time-consuming and costly, repurposing offers a faster and more economical approach since safety and pharmacological data are already available. Successful examples such as aspirin, sildenafil, and thalidomide demonstrate its potential, while the COVID-19 pandemic further highlighted its value with drugs like Remdesivir and Dexamethasone. With advances in computational tools and artificial intelligence, drug repurposing is emerging as a vital strategy to meet unmet medical needs in modern healthcare.

2. Importance of Drug Repurposing

The conventional pathway for drug development takes 10–15 years and requires billions of dollars in investment. Despite this, many drug candidates fail during clinical trials due to safety or efficacy concerns. Repurposing offers a practical solution by using compounds with established safety records, thereby reducing risk and time to market. Examples of drug repurposing has been given in Table 1.

Table 1: An example of successful Drug Repurposing

Drug	Existing use	Use after Repurposing
Aspirin	Pain and fever relief	Prevention of blood clots/MI
Sildenafil	Hypertension /Angina	Erectile dysfunction

3. Methodologies in Drug Repurposing

- Experimental Approaches: Laboratory-based studies, including in vitro and in vivo testing, to assess drug activity against new disease targets.
- Computational Approaches: Use of AI, molecular docking, network pharmacology, and big data analytics to predict novel drug-disease associations. These tools help in screening vast databases such as Drug Bank, PubChem, and Repurpose DB.

4. Types of Drug Repurposing

a) On-target repurposing: It refers to a type of drug repurposing where the existing drug targets the same biological pathway or molecular target in the new indication as it did in the original indication. The drug's mechanism of action remains the same, but it is used to treat a different disease or condition.

b) Off-target repurposing: It refers to a type of drug repurposing where the existing drug is found to have therapeutic effects for a new indication through a different biological pathway or molecular target than its original mechanism of action. In this case, the drug's new therapeutic effect is attributed to interactions with unintended targets or pathways.

5. Benefits of Drug Repurposing

Drug repurposing, also known as drug repositioning, offers significant advantages in modern pharmaceutical research and development. Unlike the traditional drug discovery process, which is time-consuming, costly, and carries a high risk of failure, drug repurposing makes use of existing drugs with known safety profiles

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to identify new therapeutic indications. This approach reduces the overall cost of development, as preclinical safety studies and Phase I clinical trials are often minimized or bypassed, thereby saving years of research and millions of dollars.

Another key benefit is the reduction of risk. Since repurposed drugs already have well-established pharmacokinetics, pharmacodynamics, and toxicity data, the uncertainty associated with their development is considerably lower compared to novel drug candidates. This accelerates the timeline from laboratory research to clinical application, making effective treatments available to patients much faster.

6. Challenges in Drug Repurposing

6.1 Patent and Intellectual Property Issues

One of the major challenges is securing intellectual property rights for repurposed drugs. Since many candidate drugs are already off-patent, companies face difficulties in obtaining exclusivity. This reduces commercial incentives for large-scale investment. As a result, research may remain limited despite strong therapeutic potential.

6.2 Regulatory and Approval Barriers

Even though the safety of an approved drug is established, new indications require regulatory approval. Authorities often demand additional preclinical and clinical evidence to ensure safety and efficacy in the new disease area. This can prolong timelines and increase costs. Thus, the expected advantage of faster market entry may be reduced.

6.3 Limited Knowledge of Drug Mechanisms

Many existing drugs have complex or poorly understood mechanisms of action. This makes it difficult to identify suitable new therapeutic targets. Without clear mechanistic insights, the chances of failure in repurposing increase. Consequently, this uncertainty slows down research progress.

7. Drug Repurposing During COVID-19

The outbreak of COVID-19 posed an urgent global health emergency, where rapid identification of effective treatments was essential. Developing a new drug or vaccine typically takes years, but the pandemic demanded immediate therapeutic solutions. In this context, drug repurposing became a highly valuable strategy, as it allowed researchers to investigate already approved or clinically tested drugs for new use against SARS-CoV-

In severe cases, the disease triggered a inflammatory state known as a “cytokine storm.” To address this, immunomodulators and anti-inflammatory drugs like dexamethasone, tocilizumab, and baricitinib were repurposed to reduce immune activation and improve survival rates. Similarly, anticoagulants were used to manage COVID-associated blood clotting disorders.

This global effort highlighted both the strengths and challenges of repurposing. On one hand, it significantly reduced development timelines by bypassing early safety studies. On the other, it revealed limitations, as not all drugs demonstrated consistent clinical efficacy despite promising laboratory results.

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8. Repurposing Natural Products or Herbal Drugs:

Repurposing refers to identifying new pharmacological actions or therapeutic indications of already known herbal drugs or natural compounds. Many herbs have multiple bioactive constituents that act on different molecular targets, making them promising candidates for drug repurposing. Unlike synthetic drugs, natural products often possess a broad spectrum of biological activities such as anti-inflammatory, antioxidant, antimicrobial, anticancer, and immunomodulatory properties.

1. Curcumin (from turmeric): traditionally used for inflammation, now explored for anticancer and neuroprotective roles.

2. Resveratrol (from grapes): initially valued for cardioprotective effects, later studied for anti-aging and anticancer applications.

3. Artemisinin (from Artemisia annua): known as an antimalarial, now investigated for anticancer and antiviral properties.

9. Role of Technology in Drug Repurposing

Technology plays a crucial role in accelerating and refining the process of drug repurposing. With advancements in computational biology, bioinformatics, and artificial intelligence, researchers can rapidly identify new therapeutic uses for existing drugs. Drug repurposing mainly relies on three key methods: computational, experimental, and data-driven approaches. The computational (in-silico) method uses molecular docking, bioinformatics, and virtual screening to predict how existing drugs may interact with new biological targets, making the process faster and more cost-effective. The experimental or phenotypic screening method involves testing drugs directly on cell cultures or animal models to observe unexpected therapeutic benefits, providing strong biological evidence but often being time-consuming and costly

10. Case Studies of Failed Drug Repurposing Attempts:

1. Hydroxychloroquine for COVID-19: Hydroxychloroquine, an antimalarial and anti-inflammatory drug, was widely investigated as a potential treatment for COVID-19 during the pandemic. Early computational and in-vitro studies suggested antiviral activity, but large-scale clinical trials (e.g., WHO Solidarity Trial) demonstrated no significant benefit in reducing mortality or disease progression. Safety concerns, such as cardiac toxicity, further limited its use, making this one of the most well-known failed repurposing attempts.

2. Bevacizumab (Avastin) for Breast Cancer: Bevacizumab, an anti-VEGF monoclonal antibody used in colon and lung cancers, was granted accelerated approval for metastatic breast cancer. However, follow-up clinical trials showed minimal improvement in overall survival and raised safety issues like hypertension and bleeding. As a result, the FDA revoked approval for this indication, marking it a failed repurposing attempt.

11. Future of Drug Repurposing

The future of drug repurposing is highly promising as it integrates modern technology, big data analytics, and personalized medicine to accelerate drug discovery. With the rising costs and long timelines of traditional drug development, repurposing offers a faster, safer, and more economical alternative. Advances in artificial intelligence (AI), machine learning, and bioinformatics will enable precise prediction of new drug–target interactions, while network pharmacology and systems biology will help in understanding complex diseases where multi-target therapies are required. The use of real-world evidence

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(RWE), electronic health records, and pharmacovigilance databases will provide deeper insights into hidden therapeutic potentials of existing drugs. Furthermore, the growing emphasis on natural products and herbal medicines opens new opportunities for discovering multi-functional agents, especially for chronic and lifestyle-related disorders. In the future, repurposing strategies are expected to align closely with personalized and precision medicine, ensuring that drugs are tailored to genetic, proteomic, and metabolic profiles of patients. With global collaboration, digital health platforms, and regulatory support, drug repurposing will continue to expand as a sustainable and innovative pathway for addressing unmet medical needs and emerging health crises.

12. Artificial Intelligence in Target Identification

Artificial Intelligence (AI) has revolutionized the identification of drug targets by enabling rapid analysis of complex biological data. Traditionally, target discovery relied on labor-intensive laboratory research, but AI-driven approaches integrate genomics, proteomics, transcriptomics, and clinical data to reveal novel targets with greater accuracy. Machine learning algorithms can uncover hidden disease–gene or drug–protein associations, while natural language processing (NLP) extracts valuable insights from scientific literature, patents, and clinical trial reports. Network pharmacology models powered by AI further help in mapping disease pathways and prioritizing drug targets.

1. DeepMind's AlphaFold → Accurately predicts 3D structures of proteins, which is critical for identifying binding sites and new drug targets.

2. BenevolentAI → Uses machine learning and biomedical data mining to discover disease-associated targets; notably identified a potential target pathway for amyotrophic lateral sclerosis (ALS).

3. IBM Watson for Drug Discovery → Applies NLP and deep learning to analyze biomedical literature and patient data, suggesting novel cancer immunotherapy targets.

13. Conclusion

Drug repurposing has become a vital approach in the pharmaceutical field, offering a faster and safer path to discover new therapeutic applications of existing drugs. It significantly reduces time, cost, and risk compared to conventional drug development. With the support of modern technologies like artificial intelligence, bioinformatics, molecular docking, and network pharmacology, the process of identifying novel drug–disease associations has become more efficient. Repurposing has already shown success in several fields, from oncology to infectious diseases, and even in managing global health emergencies such as COVID-19. At the same time, failed attempts highlight the importance of rigorous validation, clinical trials, and careful safety assessment. Challenges related to intellectual property rights, regulatory guidelines, and commercial viability still remain barriers to wider adoption. However, the growing focus on personalized medicine and integration of real-world data will further strengthen the potential of this strategy. Herbal and natural products also provide a vast resource for future repurposing research due to their multi-target activities. Ultimately, drug repurposing represents not just a cost-effective alternative but also an innovative and sustainable solution to meet unmet medical needs.

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Chapter 5

Artificial Intelligence in Pharmacy: The Future of Drug Design

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Abstract

Artificial Intelligence (AI) is rapidly transforming the pharmaceutical landscape, particularly in drug design and development. By leveraging machine learning, deep learning, and natural language processing, AI enables the analysis of vast chemical and biological datasets to accelerate drug discovery, reduce costs, and enhance therapeutic precision. AI-driven approaches support target identification, lead optimization, and predictive modeling, while advanced techniques like generative adversarial networks and reinforcement learning facilitate de novo molecular design. In toxicology and pharmacokinetics, AI predicts ADMET properties and simulates biological interactions to minimize late-stage failures and improve patient safety. Clinical trials benefit from AI through optimized patient recruitment, response prediction, and real-time monitoring. Trailblazing platforms like IBM Watson, Atomwise, BenevolentAI, and AlphaFold epitomize the transformative fusion of artificial intelligence with pharmaceutical innovation, streamlining everything from molecular discovery to clinical strategy. Despite its

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promise, AI faces challenges including data quality, model interpretability, algorithmic bias, lack of standardization, and regulatory hurdles. The infusion of AI into pharmaceutical domains is accompanied by enduring ethical dilemmas, notably those concerning the sanctity of personal data and the contested ownership of algorithmic outputs. Addressing these limitations is crucial for scalable, equitable, and trustworthy AI adoption in drug development. As the field evolves, interdisciplinary collaboration and robust validation frameworks will be essential to fully realize AI's potential in revolutionizing pharmacy.

Keywords: Artificial Intelligence; Drug Discovery; Machine Learning; Pharmacokinetics; Molecular Modeling;

1. Introduction

Artificial Intelligence has emerged as a paradigm-shifting catalyst in pharmaceutical sciences, revolutionizing methodologies from compound screening to therapeutic personalization. Its integration into drug design and development is accelerating the discovery process, reducing costs, and improving the precision of therapeutic interventions. AI encompasses machine learning (ML), deep learning (DL), natural language processing (NLP), and other computational techniques that analyse large datasets to uncover patterns and predict outcomes.

2. Role of AI in Drug Discovery

Artificial Intelligence (AI) is playing a transformative role in modern drug discovery by accelerating the identification, design, and development of novel therapeutics. Through advanced algorithms, AI enables the rapid analysis of massive biological and chemical datasets, allowing researchers to predict drug-target interactions, optimize lead compounds, and assess pharmacokinetics and toxicity profiles with greater accuracy. Machine learning models are also being used to repurpose existing drugs for new indications, reducing both time and cost in early-stage research. Furthermore, AI-driven platforms integrate genomics, proteomics, and clinical data to support precision medicine, ensuring therapies are tailored to specific patient populations.

2.1 Target Identification

Target identification is the initial and most critical step in the drug discovery process, where researchers determine the specific biological molecules, such as proteins, enzymes, or genes that are responsible for the onset or progression of a disease. The goal is to identify and validate a target whose modulation—through inhibition, activation, or regulation—can bring about a therapeutic effect. Modern approaches combine genomics, proteomics, bioinformatics, and AI-driven data analysis to uncover novel targets with higher accuracy and efficiency. Proper target identification is essential, as it lays the foundation for the entire drug development pipeline; an incorrect or poorly validated target can lead to costly failures in later stages.

2.2 Lead Compound Identification

Lead compound identification is a crucial stage in drug discovery, where potential chemical entities are screened and selected for their ability to interact effectively with a validated biological target. The objective is to find small molecules, peptides, or biologics that demonstrate promising activity, selectivity, and safety profiles against the target of interest. This process typically involves high-throughput screening of large compound libraries, computer-aided drug design,

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and structure–activity relationship (SAR) studies to refine candidate molecules.

2.3 Structure-Based Drug Design

Structure-based drug design (SBDD) is a rational approach to drug discovery that relies on detailed knowledge of the three-dimensional (3D) structure of a biological target, usually obtained through techniques like X-ray crystallography, NMR spectroscopy, or cryo-electron microscopy. In this method, the structural information of the target protein or enzyme is used to design and optimize small molecules that can specifically bind to its active or allosteric sites. Computational tools such as molecular docking, virtual screening, and molecular dynamics simulations are widely employed to predict binding interactions and optimize compound stability, potency, and selectivity. By directly visualizing how potential drug molecules interact with the target at the atomic level, SBDD reduces trial-and-error, accelerates lead optimization, and improves the chances of developing safe and effective therapeutics. This approach is especially valuable in designing inhibitors for enzymes, receptors, and viral proteins in complex diseases.

3. AI in Drug Design and Molecular Modelling

Artificial Intelligence (AI) is revolutionizing drug design and molecular modelling by enabling faster, more accurate, and cost-effective approaches to developing novel therapeutics. In drug design, AI algorithms analyse vast chemical and biological datasets to predict drug–target interactions, optimize lead structures, and assess absorption, distribution, metabolism, excretion, and toxicity (ADMET) properties at early stages. Machine learning and deep learning models are particularly effective in identifying molecular patterns, generating de novo compounds, and refining structure–activity relationships (SAR). In molecular modelling, AI enhances traditional computational techniques such as molecular docking, virtual screening, and molecular dynamics simulations by improving binding affinity predictions and exploring conformational changes more efficiently. Generative AI models, such as deep generative networks and reinforcement learning, are now used to design novel molecules with specific pharmacological profiles.

4. Toxicology Predictive and Pharmacokinetics

Toxicology prediction and pharmacokinetics are two essential components in drug discovery and development, aimed at ensuring the safety and efficacy of potential drug candidates. Toxicology prediction uses computational models, in vitro assays, and increasingly artificial intelligence to forecast the potential harmful effects of a compound before clinical testing. Predictive toxicology evaluates risks such as genotoxicity, hepatotoxicity, cardiotoxicity, or neurotoxicity by analysing chemical structure, biological activity, and molecular interactions. Early identification of toxic liabilities prevents costly late-stage failures and improves patient safety. Pharmacokinetics (PK), on the other hand, studies how a drug is absorbed, distributed, metabolized, and excreted (ADME) in the body. Predictive pharmacokinetics employs computational modelling, simulations, and in silico tools to estimate drug bioavailability, half-life, and clearance rates. Accurate PK predictions are vital for optimizing dosage forms, determining therapeutic windows, and minimizing side effects .Together, predictive toxicology and pharmacokinetics guide rational drug design by balancing efficacy with safety, ensuring that only promising candidates progress into preclinical and clinical studies.

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5. AI in Clinical Trials

Artificial Intelligence (AI) is reshaping clinical trials by improving efficiency, accuracy, and patient outcomes across all phases of drug development. AI-driven algorithms can identify and recruit eligible participants more effectively by analysing electronic health records, genetic data, and real-world evidence, thereby reducing delays and ensuring diverse patient populations. In trial design, AI models simulate outcomes and optimize protocols to minimize costs and enhance reliability. During the trial process, machine learning tools monitor patient data in real-time, detect adverse events earlier, and predict treatment responses, which supports adaptive trial designs and personalized therapies. Natural language processing further streamlines regulatory documentation and reporting, reducing administrative burdens. By integrating vast amounts of clinical, genomic, and patient-generated data, AI not only accelerates decision-making but also improves trial success rates, ultimately leading to safer and more effective therapeutics reaching patients faster.

6. AI Platforms and Tools in Pharmacy

Artificial Intelligence (AI) is increasingly embedded into various platforms and tools in pharmacy, streamlining processes from research to patient care. In drug discovery and development, AI-powered platforms such as Atomwise, Insilico Medicine, and BenevolentAI use deep learning to predict drug–target interactions, design novel compounds, and optimize lead molecules. For molecular modelling and simulations, tools like DeepChem and Schrodinger AI modules assist in virtual screening, structure-based drug design, and pharmacokinetic predictions. In clinical trials, AI-driven platforms such as Deep6AI and TriNetX improve patient recruitment, monitor trial data in real time, and support adaptive study designs. In pharmacy practice, AI chatbots and decision-support tools assist pharmacists in personalized medication counselling, drug–drug interaction checks, and adherence monitoring. Furthermore, AI-integrated platforms in pharmacovigilance analyse large-scale post-marketing data to detect adverse drug reactions earlier.

7. AI in Preclinical and Clinical Development

Artificial Intelligence (AI) is becoming an integral part of both preclinical and clinical development, transforming how new drugs are discovered, tested, and brought to market. In the preclinical stage, AI accelerates target identification, predicts lead compound activity, and evaluates pharmacokinetics and toxicology using advanced computational models. Machine learning algorithms analyse complex omics data, animal study results, and in vitro experiments to predict safety and efficacy before moving to human trials, thereby reducing costs and minimizing animal testing. In the clinical stage, AI enhances patient recruitment by analysing electronic health records and genetic data, supports adaptive trial designs, and enables real-time monitoring of adverse events and treatment responses. Predictive models help optimize dosing regimens, while natural language processing automates data extraction for regulatory submissions. By bridging preclinical predictions with clinical evidence, AI improves decision-making, shortens development timelines, and increases the probability of success in delivering safe and effective therapies.

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8. Ethical and Regulatory Considerations

Ethical and regulatory considerations play a vital role in guiding the safe and responsible application of Artificial Intelligence (AI) in drug discovery and pharmacy. From an ethical perspective, concerns include data privacy, informed consent, transparency, and potential algorithmic bias. Since AI models rely on vast amounts of patient and clinical data, ensuring confidentiality, preventing misuse of sensitive health information, and maintaining fairness in decision-making are critical. Ethical use also demands explainability of AI decisions, especially in clinical settings where patient outcomes are directly affected. On the regulatory side, agencies such as the FDA, EMA, and WHO are developing frameworks to evaluate AI-based tools for safety, reliability, and compliance.

9. Future Perspectives

The future perspective of AI in pharmacy and drug discovery is highly promising, with the potential to transform every stage of the pharmaceutical pipeline. Advancements in generative AI, deep learning, and quantum computing are expected to design novel drug molecules with greater precision and speed, significantly reducing the time and cost of development. Integration of multi-omics data (genomics, proteomics, metabolomics) with AI will enable highly personalized and predictive medicine, tailoring treatments to individual patients. In clinical settings, AI-driven platforms will enhance real-world evidence analysis, remote patient monitoring, and digital therapeutics, improving both efficacy and accessibility of healthcare. Regulatory authorities are also moving toward adaptive frameworks that can accommodate rapid AI innovations while ensuring patient safety and ethical compliance.

10. Challenges in AI Implementation

The implementation of Artificial Intelligence (AI) in pharmacy and drug discovery faces several significant challenges despite its rapid progress. One of the primary issues is data quality and availability, as AI models require large, well-curated datasets, but clinical and pharmaceutical data are often fragmented, unstructured, or confidential. Another challenge is interpretability and transparency—many AI algorithms, especially deep learning models, function as "black boxes," making it difficult for researchers, regulators, and clinicians to fully understand or trust their predictions. Integration with existing systems is also complex, as healthcare and pharmaceutical infrastructures vary widely in technology readiness. Furthermore, there are ethical and regulatory hurdles, including patient data privacy, algorithmic bias, and lack of standardized global guidelines for AI-driven tools. Finally, high costs, need for skilled professionals, and resistance to adoption in traditional pharmaceutical settings hinder large-scale implementation. Addressing these challenges will be essential to fully harness AI's potential in advancing drug discovery and pharmacy practice.

11. Conclusion

Artificial Intelligence (AI) has emerged as a transformative force in pharmacy, drug discovery, and healthcare, offering innovative solutions to accelerate research, reduce costs, and improve patient outcomes. From target identification and lead optimization to predictive toxicology, clinical trials, and personalized medicine, AI is streamlining complex processes that traditionally required years of effort. However, challenges such as data quality, interpretability, regulatory approval, and ethical concerns must be carefully

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addressed to ensure responsible and reliable use. With continuous advancements in machine learning, big data analytics, and computational tools, the future of AI in pharmacy lies in creating more precise, efficient, and patient-centered therapies. Ultimately, AI is not a replacement for human expertise but a powerful collaborator, enabling researchers, clinicians, and pharmacists to deliver safer and more effective healthcare solutions worldwide.

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Chapter 6

Gastro-retentive Floating System for Controlled Release: A Natural Polymer Approach

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Abstract

Gastro retentive Drug Delivery System (GRDDS) has gained significant attention due to its ability to reduce dosing frequency, enhance bioavailability, and improve patient compliance. In this study, a novel plant-based, pH-sensitive, and controlled swelling GRDDS was developed using Amla and Aloe vera hydrogel combined with cellulose for the sustained release. The system is designed as a floating drug delivery system, which possesses a bulk density lower than gastric fluids, allowing it to remain buoyant in the stomach and thereby extend gastric residence time. The formulation achieved a floating lag time of less than 1 minute and maintained buoyancy for over 12 hours. Sustained drug release was observed for more than 12 hours, following the Hixson-Crowell model and non-Fickian diffusion, indicating a combined mechanism of diffusion and erosion. In vivo pharmacokinetic studies confirmed the extended release and absorption of LEVO. Furthermore, toxicity evaluations demonstrated the non-toxic nature of the hydrogel-based system .Overall, this approach represents a promising strategy for oral delivery of antibiotics like LEVO by minimizing dosing frequency and enhancing therapeutic outcomes. Its natural polymer base also contributes to

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better biocompatibility and patient safety, highlighting its potential for clinical application.

Keywords: Controlled release; Floating tablet formulation; Microcrystalline cellulose; Natural hydrogel; Pharmacokinetics;

INTRODUCTION:

To extend the retention period, several attempts have been made to keep the dosage form in the stomach. These initiatives include the introduction of floating dosage forms (swelling or expanding systems and gas-generating systems), mucoadhesive systems, high-density systems, modified shape systems, gastric-emptying delaying devices, and co-administration of drugs that delay the emptying of the stomach. These efforts include the use of mucoadhesive systems, high-density systems, modified shape systems, gastric-emptying delaying devices, co-administration of gastric-emptying delaying medications, and floating dosage forms (gas-generating systems and swelling or expanding systems). The floating dosage forms have been the most widely utilized of these. The oral route is increasingly being used for the delivery of therapeutic agents because the low cost of the therapy and ease of administration lead to high levels of patient compliance. More than 50% of the drug delivery systems available in the market are oral drug delivery systems. Floating systems or hydro dynamically controlled systems are low-density systems that have sufficient buoyancy to float over the gastric contents and remain buoyant in the stomach without affecting the gastric emptying rate for a prolonged period of time. While the system is floating on the gastric contents, the drug is released slowly at the desired rate from the system. After release of drug, the residual system is emptied from the stomach. This results in an increased GRT and a better control of the fluctuations in plasma drug concentration. However, besides a minimal gastric content needed to allow the proper achievement of the buoyancy retention principle, a minimal level of floating force (F) is also required to keep the dosage form reliably buoyant on the surface of the meal. Many buoyant systems have been developed based on granules, powders, capsules, tablets, laminated films and hollow microspheres. Aloe Vera contains compounds polyphenols, aloin, and acemannan, which have been shown to inhibit the growth of various bacteria including Staphylococcus aureus and Escherichia coli. This compound can disrupt bacterial cell structure and function, and preventing them from multiplying and causing infection.

Amla has a rich content of vitamin C, Antioxidants, and other Bioactive compounds which reduce inflammation and directly inhibit bacterial growth. Amla is an excellent source of vitamin C, which is known to enhance the activity of phagocytes, Immune cells that engulf in destroy harmful pathogens. Anti-oxidants that help neutralize free radicals, which can damage cells and contribute to inflammation, making the body more susceptible to infections.

USES

Aloe Vera has a wound healing and anti-inflammatory effects, make it a valuable natural remedy for managing and preventing bacterial infections especially in the context of skin and wound care. Particularly at higher concentrations, has demonstrated significant anti-bacterial activity against bacterial strains. while it has anti-inflammatory and collagen stimulating properties further promote healing.

Amla is used for boosting the immune system and potentially inhibiting the growth of certain bacteria additionally amla's anti-

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oxidant and anti-inflammatory properties can aid in the body's recovery from infections. It can also help in the treatment of UTI'S potentially inhibiting the growth of bacteria in urinary tract.

Table 1 shows the various criteria used to distinguish between the conventional and gastro-retentive drug delivery systems.

RELATIVE PARAMETERS	CONVENTIONAL DRUG DELIVERY SYSTEM	GASTRO RETENTIVE DRUG DELIVERY SYSTEM
TOXICITY	High risk of toxicity	Very low risk of toxicity
PATIENT COMPLIANCE	Low	Improved
DRUGS WITH POOR SOLUBILITY AND HIGH Ph	Not suitable for delivery of drugs with narrow absorption window in the small intestine region	Suitable for delivery of drugs with narrow absorption window in the small intestine region
DRUGS ACTING LOCALLY ACTING IN THE STOMACH	Not much advantageous for drug shaving rapid absorption through GIT	Very much advantageous of drugs acting locally in the stomach
DOSE DUMPING	No risk of dose dumping	Possibility of dose dumping

BASIC GIT PHYSIOLOGY:

Anatomically the stomach is divided in to three regions:

- Fundus
- Body
- Antrum (pylorus).

The proximal part made of fundus and body acts as a reservoir for undigested materials, whereas the antrum is the main site for mixing motions and acts as a pump for gastric emptying by propelling actions. Gastric emptying occurs in both the fasting and fed states.

During the fasting state an inter-digestive series of electrical events take place which cycle both through stomach and intestine every 2-3 hrs, which is called as inter-digestive myloelectric cycle or migrating myloelectric cycle (MMC) which is further divided in to four phases.

After the ingestion of a mixed meal, the pattern of contractions changes from fasted to that of fed state which is also termed as digestive motility pattern.

Phase 1-(Basic phase)-last from 30-60 minutes with rare contractions.

Phase 2-(Preburst phase)-last for 20-40 minutes with intermittent action potential and contractions.

Phase 3-(Burst phase) - last for 10-20 minutes which includes intense and regular contractions for short period.

Phase 4-last for 0-5minutes and occurs between phase 2 and 1 of 2 consecutive cycles.

TYPES OF FLOATING DRUG DELIVERY SYSTEMS:

EFFERVESCENT SYSTEMS:

It is a type of drug delivery system can be made to float in the stomach by incorporating a floating chamber that may be filled with air, vacuum, or inert gas.

NON-EFFERVESCENT SYSTEMS:A non-effervescent system is a floating drug delivery system that retains buoyancy in the stomach by using swelling polymers, gel-forming agents, or low-density materials, instead of relying on carbon dioxide release

RAFT-FORMING SYSTEMS:A raft-forming system forms a viscous, gel-like floating barrier (raft) at the top of the stomach contents when

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it comes in contact with gastric fluid. This raft prevents the backflow (reflux) of acidic gastric contents into the esophagus.

MECHANISM OF FLOATING SYSTEM:

The principal mechanism of floatation to achieve gastric retention. Floating drug delivery systems (FDDS) stay afloat in the stomach for an extended amount of time without influencing the gastric emptying rate Buoyant on the meal's surface, a minimal level of floating force (F) is also necessary in addition to a minimal gastric content that permits the correct realization of the buoyancy retention principle.

where F is the total vertical force

Df is the fluid density

Ds is the object density

v is the volume

g is the acceleration due to gravity

because their bulk density is lower than that of gastric fluids. As a result, the variations in plasma drug concentration are better controlled and the GRT is raised. However, to maintain the dosage form consistently

EVALUATION PARAMETERS OF FLOATING DRUG DELIVERY SYSTEM:

WEIGHT VARIATION TEST:

The average weight of 20 tablets is taken and the weight deviation in each tablet should be within ±5%. Not more than two individual tablets should deviate from average weight by more than the percentage allowed.

DRUG CONTENT UNIFORMITY:

The amount of drug present should be 85-115% of labelled amount

DRUG CONTENT % = (Amount of drug found / theoretical of drug content) X 100

SWELLING INDEX:

The swelling index is a measure of water uptake ability of the dosage form

Swelling Index (%) = (Wt – W0/W0)X100

Where, Wt is the weight of swollen dosage form at time t

W0 is the initial dry weight

FLOATING LAG TIME:

The floating lag time is defined as the time taken by the dosage form to rise to the surface of the dissolution medium and begin to float after being placed in the medium. The floating lag time should be less than 1 minute.

TOTAL FLOATING TIME:

The Total floating time is the duration for which the dosage form remains buoyant on the surface of the dissolution medium after its initial floating. The total floating time should be greater than 12 hours or should be in 12 hours.

IN VITRO DRUG RELEASE:

The In vitro drug release refers to dissolution and diffusion of active pharmaceutical ingredient from a floating dosage form into a simulated gastrointestinal medium under controlled laboratory conditions.

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DRUG RELEASE KINETICS:

The Drug release kinetics describes the rate and mechanism by which the active pharmaceutical ingredient (API) is released from the floating drug delivery system (FDDS) over time in simulated gastric conditions. Common drug release kinetic models are Zero order, First order, Higuchi model, Hixson-Crowell, Korsmeyer-Peppas.

MUCOADHESIVE STRENGTH (if applicable):

Mucoadhesive strength is the force required to detach a drug formulation from a mucosal surface

STABILITY STUDY:

The stability studies are conducted to assess how the quality of a drug formulation varies over time under the influence of environmental factors such as temperature, humidity and light.

FACTORS AFFECTING FLOATING DRUG DELIVERY SYSTEM:

Density: Density is a prerequisite for floating. The dosage form's density must be lower than the gastric content. Thus, to exhibit the floating property, the density must be less than 1 gm/ml. Therefore, while higher density dosage forms sink to the bottom of the stomach, those with a density lower than the gastric content can easily float on the surface.

Shape: When compared to other shapes, tetrahedron and ring-shaped devices with flexural modules of 48 and 22.5 kg/sq in (KSI) are said to have superior floating and 90% to 100% retention at 24 hours. Size: More time is spent in the stomach by a dosage form with a diameter greater than 7.5 mm

Fed or Unfed State: Every one and a half to two hours, there are intense bursts of motor activity that define the gastric motility during a fast. If the formulation time and the MMC are the same, the unit's GRT may be rather short. However, because it removes undigested material from the stomach during the fast state, the MMC is delayed and the GRT is prolonged.

Viscosity of Polymers: The floating characteristics of FDDS and drug release are significantly impacted by the viscosity of different polymer grades and their interactions. When it comes to improving the floating properties of the dosage form, low viscosity polymers—like HPMC K100 LV—work better than high viscosity polymers, like HPMC K4M. Furthermore, it was demonstrated that a decrease in the release rate was also linked to an increase in the polymer's viscosity.

ADVANTAGES AND DISADVANTAGES:

ADVANTAGES	DISADVANTAGES
• Improved drug absorption, Utilization and thereby enhancing bioavailability. • Delivery of drugs for local action in the stomach. • Reduction in dosing frequency • Higher shelf life • Low healthcare cost • Better patient acceptance and compliance	• Drugs having irritant effects on gastric mucosa are not suitable candidates for FDDS. • Floating forms shouldn't be administered to patients right before bed. • Not suitable for drugs that have solubility or stability problem in GIT. • Not suitable for colon specific delivery of drugs

CONCLUSION:

The goal of the floating drug delivery system (FDDS) is to increase the drug's bioavailability in the stomach area while maintaining small absorption window Floating drug delivery systems (FDDS) enhance gastric retention, improving the absorption and bioavailability of drugs that act in the stomach or upper intestine. They are beneficial for treating gastric disorders and ensuring controlled or sustained drug release. FDDS include effervescent, non-effervescent, and raft-

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forming systems, each with unique mechanisms. FDDS aids in lowering the dosage frequency. Though challenges like variability in gastric emptying and formulation design exist, FDDS remain a valuable strategy in targeted oral drug delivery.

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Chapter 7

Review on recent wearable technology for respiration monitoring

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Abstract

Respiration is one of the most vital parameters of human body. The advancements of the technology had improved the way of detecting the respiration through wireless technology. The wireless technology mainly uses wearable and portable sensors which has its unique featured properties in monitoring the respiration rate. The proposed review paper describes the recently discovered wireless technology the has improved the continuous monitoring of respiration rate based on the angular velocity, flexible capacitive pressure sensor and non-contact capacitive electrode. The working principle of all the determined technologies varied based on the types of sensors used to monitor the respiration rate

Keywords: wearable technology, respiration monitoring, inertial sensor, flexible capacitive pressure sensor, non-contact capacitive based electrode.

INTRODUCTION:

The development of current technologies has been improved more faster in the field of healthcare. Monitoring the vital parameters of

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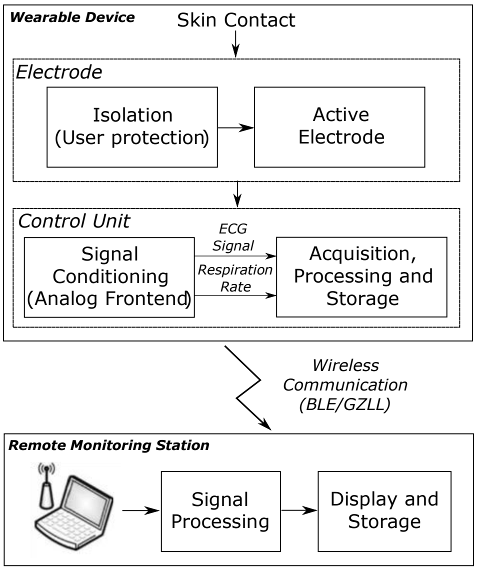
human body accurately in motion or during daily activities are challenging tasks in present life. Respiration is one of the important parameters of human bodies which is monitored continuously to detect sleep disorders (i.e., sleep apnea) and asthma which is common respiratory diseases in the world. The proposed review paper describes the working and the principles used for monitoring the respiration rate by using different types of sensors.

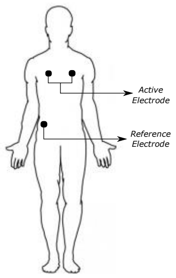
LITERATURE REVIEW:

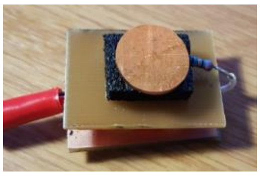
Wireless Capacitive Based ECG Sensing for Feature Extraction and Mobile Health Monitoring by Johan Wannenburg:



In this paper the author have designed a wireless device which is capable of monitoring both ECG and respiration rate(RR). The monitoring system uses contactless capacitive based electrode which is an active electrode and an analogue conditioning circuit. The signals are transferred from device to mobile using BLE(Bluetooth technology). BLE uses low power communication with the remote server. The introduction is basically about the ECG and RR which helps in understanding the needs of the parameters to develop this wearable device. Overview of this paper defines complete hardware properties of the wearable device.

The device is responsible for monitoring ECG and RR by using two sub systems. They are wearable device and remote monitoring station which uses Bluetooth technology. The device is battery powered and capable of transmitting the acquisition data to the remote monitoring systems.





The device set up is made in such a way that the extraction of ECG related features and RR can be monitored with a complete protection using isolation. The electrodes are place in chest using a strap which measures both the parameters through capacitively coupled signals. The signals are acquired in analogue signal and converted into digital signals using ADC. Then the signals are transferred to remote monitoring systems and observed by physician. The devices transmit both parameters to remote monitoring system but the author aims in developing this device as a promising one to monitor accurate data in future.

A Novel Signal Acquisition System for Wearable Respiratory Monitoring by Guo Dan:

In this research article, a new method of obtaining the respiratory sensing for monitoring the continuous acquisition of respiratory signals based on the angular velocity. The sternum or breastbone and the trachea of both male or female is the suitable area for placing the wearable device due to its insensitivity. The respiration detection

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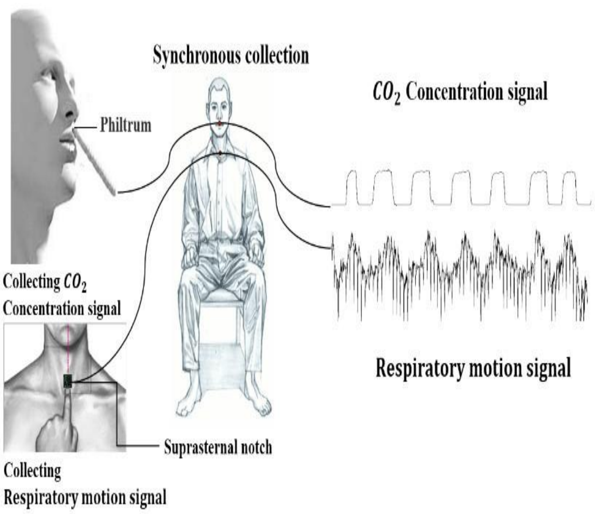
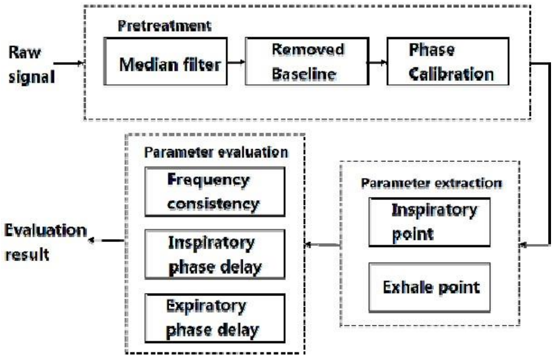
mechanism of the wearable device works under the Euler's angle formula which finds out the exact position of the fixed-point rotation from the number of parameters namely pitch angle, roll angle and the yaw angle. The experimental set-up consists of two test-beds in which the first test-bed is a inertial platform and the second test-bed is a carbon-dioxide (CO2) concentration setup. The CO2 concentration is used to sense the accuracy of the inertial sensor platform because it is considered as gold standard reference for synchronizing the acquisition of both former and later platforms. RESPLIVE/TiniStream module from Witleaf Co.Ltd., is used in CO2 concentration platform for opening the path for signal acquisition from port to PC at sample frequency of 25Hz. The inertial sensor platform uses INVENSENSOR MPU6050 which is small, low-cost and power efficient. The sample frequency of inertial sensor platform is double than that of CO2 concentration platform (i.e. 50Hz).



The inertial sensor in placed on the targeted area by using a double-sided tape. A nasal cannula is directly placed below the nasal cavity for detecting the air flow. The acquired data is transmitted from device to the PC. The test was done on 10 healthy subjects which includes 5 males and 5 females. Single channel angular velocity module collected the respiratory signal from the targeted area in which it showed three unique frequencies. They are normal, high and low frequency. These unique frequencies analyses the respiration rate (i.e., breath at normal frequency shows 0.25Hz, at high frequency it shows 0.4Hz and at low frequency it shows 0.15Hz). The two steps algorithm is discovered in this paper. Preprocessing is done to eliminate noise and phase differences. Calculation of respiration parameters like inspiration and expiration is performed in the second step. Comparing with the tradition method which uses a nasal cannula for detection the respiration signals, the proposed wearable method provides more comfort to the patient.



CONCLUSION:

In this paper wearable technology which uses inertial sensor, flexible capacitive pressure sensor, non-contact capacitive based electrode for monitoring the respiration rate or respiration signals have been reviewed. The specifications and working of device changes based on the type of sensor used. The reviewed papers show's faster acquisition of respiration signals in motion. The further approach will be done on wireless technologies which are used for monitoring respiration in motion will be studied and reviewed in future.

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Chapter 8

Smart Prosthetic Thumb controlled by EMG Signals: Design and Build

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Abstract: This research work presents the design and construction of thumb amputation or dysfunction a natural and functional replacement. The proposed design incorporates a sophisticated control mechanism that interprets the EMG signals and translates them into corresponding thumb movements. A combination of 3D printing and bioengineered materials is employed to fabricate the prosthetic, ensuring a lightweight and customizable solution. Preliminary tests with amputee subjects demonstrate promising results, indicating improved dexterity and usability. The artificial thumb prosthesis offers a novel approach to enhance the quality of life for individuals with thumb-related impairments advancement in prosthetic technology is led to the development.

Keywords: *EMG sensor, servo motor, prosthetic thumb, micro controller, sensor module kit*

INTRODUCTION

In recent years, the intersection of biomedical engineering and robotics has led to remarkable advancements in the field of prosthetics. The loss or impairment of a thumb can significantly impact a person's ability to perform everyday tasks, leading to challenges in independence, productivity, and quality of life. In response to this problem, the present project aims to design and construct an artificial thumb prosthetic that can be controlled by the EMG signals. This innovative solution seeks to restore hand functionality and empower individuals who have experienced thumb loss due to injury, amputation, or congenital conditions.

The artificial thumb prosthetic will be a technologically advanced device that mimics the movement and functionality of a natural thumb. This biofeedback-based approach ensures a more intuitive and natural control over the prosthetic, making it an extension of the user's hand. Beyond the technical aspects, the project aims to prioritize user comfort, safety, and adaptability. The prosthetic will be designed with the user's needs in mind, providing customization options to fit individual hand sizes and functional requirements. Additionally, safety features will be incorporated to prevent any unintended movements or harm to the user. An innovative artificial thumb prosthesis that utilizes the EMG signals for control. The prosthesis aims to provide individuals with

An EMG-based prosthetic bio-thumb represents a remarkable fusion of advanced technology and biomedical science, offering the potential to revolutionize the field of prosthetics. This cutting-edge innovation integrates real time EMG sensor module kit with 3D printing technology to create a highly functional and adaptive solution for individuals with limb loss. In this introduction, we will explore the key components, benefits, and implications of an EMG-based prosthetic bio-thumb

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Restoration of Functionality: The thumb plays a crucial role in hand dexterity and is essential for performing numerous everyday tasks, such as grasping objects, writing, and manipulating tools. By creating an artificial thumb, individuals with thumb loss or impairment can regain a level of functionality and independence that may have been otherwise difficult or impossible to achieve.

Improved Quality of Life: Losing a thumb can be emotionally and psychologically challenging. It affects a person's ability to participate in activities they previously enjoyed, impacting their self-esteem and mental well-being. Providing a functional and aesthetically pleasing prosthetic can greatly improve their quality of life and overall happiness.

Education and employment opportunities can also be affected by the absence of thumbs. The traditional educational and work environments may not always be accessible to individuals with this condition. However, advancements in assistive technology and the growing awareness of diversity and inclusion have improved access to education and employment for people with disabilities. Many individuals without thumbs have successfully pursued careers in various fields, proving that determination and adaptability can overcome physical limitations. Additionally, personal relationships and social interactions can be impacted. People may be curious, well-intentioned, or unintentionally insensitive when interacting with someone without thumbs. It's crucial for both the individual and society to foster understanding, respect, and empathy to create a more inclusive and accepting environment.

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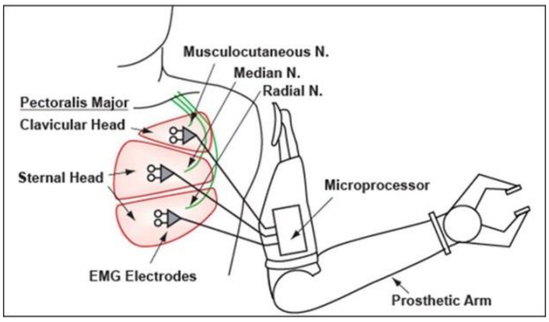

Figure 1.1 Person with EMG Sensor and Prosthetic Bio Arm

Furthermore, individuals without thumbs may encounter challenges related to healthcare and medical expenses. Prosthetic limbs, rehabilitation, and other specialized treatments can be expensive, and access to quality healthcare can vary based on geographical location and economic factors. This highlights the importance of healthcare accessibility and support systems for individuals with disabilities. Despite the numerous challenges, people without thumbs often demonstrate remarkable resilience and adaptability. They learn to use their feet, mouths, or other body parts for tasks that would typically require thumbs. They engage in sports and hobbies, and they pursue their passions with determination. Many have become advocates for disability rights, promoting inclusivity and raising awareness about the capabilities of individuals with disabilities. In conclusion, individuals without thumbs face a wide range of physical, emotional, and societal challenges. However, with determination, adaptability, and support from society, they can overcome these challenges and lead fulfilling lives. It is essential for us as a society to promote inclusivity, accessibility, and understanding to ensure that individuals without thumbs, and those with other disabilities, can participate fully in all aspects of life.

II. Methodology

A. EMG Signal Acquisition

The first step in the proposed work is to develop a robust EMG signal acquisition system. This system will consist of surface electrodes that adhere to the skin above the residual muscles of the user's limb. The electrodes will capture EMG signals generated during muscle contractions and transmit this data to a microcontroller or a computer for processing.

Prosthetic Thumb Prototype

A functional prosthetic thumb prototype will be developed, integrating the Arduino and microcontroller for EMG signal decoding. The prosthetic thumb will be designed to replicate the natural movements of a human thumb, offering a wide range of motion, including wrist rotation, elbow flexion/extension, and finger dexterity. The prototype will be lightweight, durable, and customizable to fit the user's

User Trials and Refinement: A critical phase of the project involves user trials. Amputee volunteers will be recruited to test the EMG-controlled prosthetic thumb in real-world scenarios. These trials will allow us to collect feedback on the system's performance, comfort, and usability. Any issues or limitations identified during the trials will be addressed in the refinement phase.

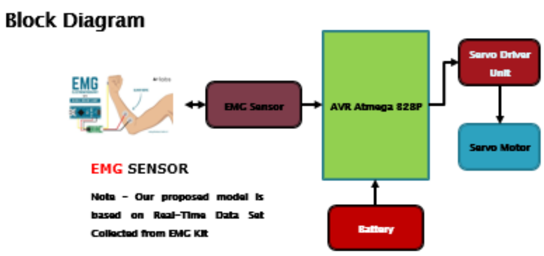

Figure 1.2

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1.2. Block diagram

COMPONENTS REQUIRED

1. ELECTRODE PADS

2. EMG MUSCLE SENSOR

3. ARDUINO

4. SERVOMOTOR

III. EMG Signal Acquisition

The acquisition of EMG signals from the muscles involves standards and protocols for electrode placement, signal processing, and data transmission. The most commonly used standards for electrode placement are those outlined by the International Society of

Electrophysiology and Kinesiology (ISEK). Signal processing methods can follow standard practices for filtering, amplification, and digitization

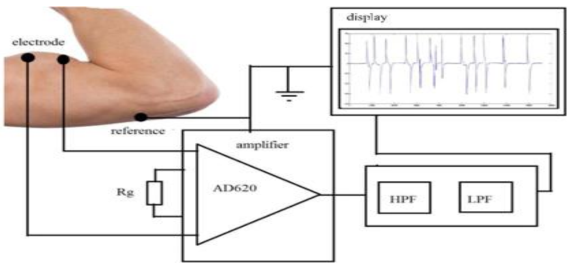


Figure 1.3 EMG signal acquisition

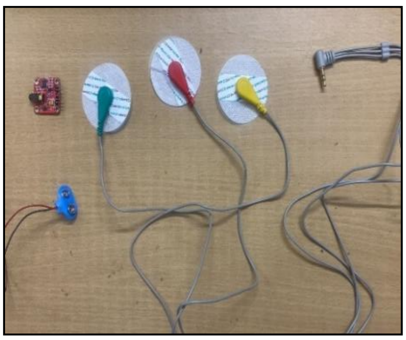


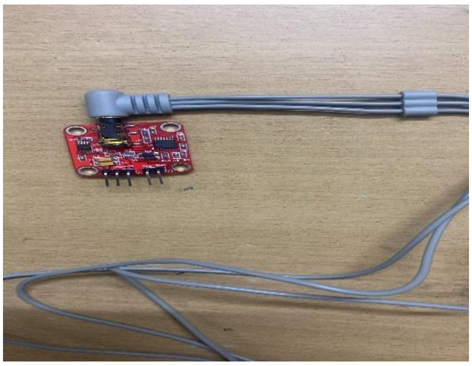
Figure 1.4

Electrode Pads

Gel electrodes are used with muscle sensor v3 to capture data. The electrode is replaced when to record for another subjects, to get the higher quality EMG signal, maintain cleanliness, and prevent the spreading of infectious diseases. This electrode has three colors, red, green and yellow —the red electrode is (ground), the yellow electrode (reference) and the green color electrode is (the EMG signal)

MUSCLE SENSOR

The Muscle Sensor that is used to record electrical potentials produced by contracting muscles. This sensor process the raw signal when records because its sequence is constructed of an instrumentation amplifier, rectifier, analog filter circuits, and an end amplifier circuit. After recording the signal, the sensor amplifies and processes the complex electrical activity of a muscle before converting it to a simple analog signal that is easily read by a microcontroller Arduino) to convert it into a digital signal.



1.5 Components and hardware prototype

Arduino UNO

Arduino UNO with ATmega328P-based microcontroller board. It contains 14 input/output digital pins (of which six can be used as PWM outputs). Arduino UNO is used to convert analog to digital

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output due to the signal produced by muscle sensor v3. Muscle sensor output was interfaced with an Arduino UNO microcontroller to record the signal on a laptop operating in battery mode for signal processing and classification .

Figure 1.6

SERVO MOTOR

A servo, short for servomechanism, is a type of device used for precision control of angular or linear position, velocity, and acceleration. It usually consists of a motor coupled to a sensor for position feedback, which is then controlled by a servo controller. The servo system is a closed-loop control system where the controller uses the feedback signal to accurately control the position or speed of the motor. This is accomplished by comparing the desired position or speed (the command signal) with the actual position or speed (the feedback signal), and then adjusting the motor’s operation to reduce the difference (the error signal).

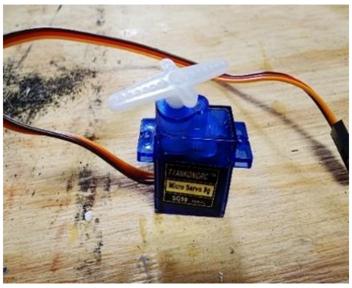

Figure 1.7

IV. RESULT AND CONCLUSION:

It's worth noting that prosthetic technology continues to advance, leading to increasingly sophisticated and functional prosthetic thumbs. These advancements aim to improve the overall quality of life for individuals who have lost their natural thumb and provide them with opportunities to participate in various aspects of life more fully. Our proposed model will surely bring a novel changed for the people who suffer to continue their routine ADLs activity

The foundation of EMG-based prosthetic thumb lies in the acquisition and processing of electromyographic signals. These signals are recorded from the residual muscles of the amputated thumb and are used to decode the user's intended movements. Current signal processing techniques have become increasingly sophisticated, allowing for accurate and real-time signal decoding.

EMG-based prosthetic thumb, augmented by Arduino and microcontroller, have come a long way in improving the lives of individuals with thumb loss. They offer greater control, enhanced functionality, and a more natural user experience. However, there are still challenges to overcome, such as cost, sensory feedback, and ease of use. The future scope of EMG-based prosthetic thumb is promising, with advancements in signal processing, biomechanical integration, sensory feedback, and cost reduction. These developments have the potential to make prosthetic thumb more accessible and user-friendly, ultimately providing a better quality of life for those who rely on them. As technology continues to advance, the prospects for EMG-based prosthetic thumb will only become more exciting, with the ultimate goal of restoring as much function and autonomy as possible to individuals with loss of thumb.

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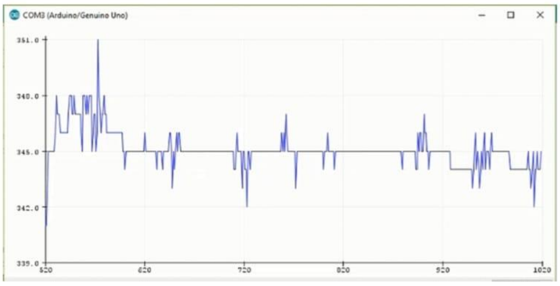

Figure 1.8

The frequency range involved in controlling a prosthetic thumb using an electromyography (EMG) module typically falls within the range of 20 Hz to 500 Hz. These contractions generate electrical signals that can be detected and used to control a prosthetic device. Read the analog signal from the EMG sensor using our controller board via analog pins.

We need to filter, amplify, or preprocess the EMG signal to extract meaningful information, like muscle activity levels or patterns.

Figure 1.9

Real-time Feedback: The Arduino Uno can provide real-time feedback to the user, which is essential for refining motor skills and ensuring safety during everyday tasks. Users can receive sensory input through vibrations, sounds, or other feedback mechanisms, enhancing their control over the prosthetic. With this setup, individuals can regain fine motor control and dexterity, enabling them to perform a wide range of once-challenging tasks. The AVR microcontroller processes the EMG signals and translates them into commands to actuate the prosthetic thumb's movements, allowing for natural and intuitive control

Position of servomotor at 90°

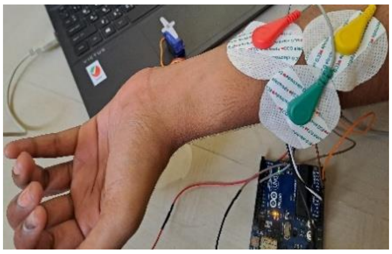

Figure 1.10

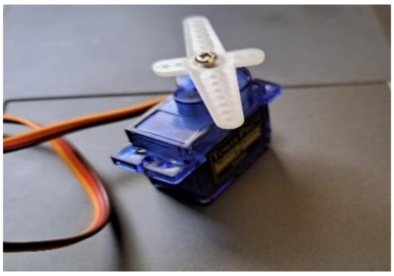

Figure 1.11

Implement feedback mechanisms to ensure the servo responds correctly to muscle activity. We may need to calibrate the system to adapt to different users or varying signal strengths.

Position of servomotor at 180°

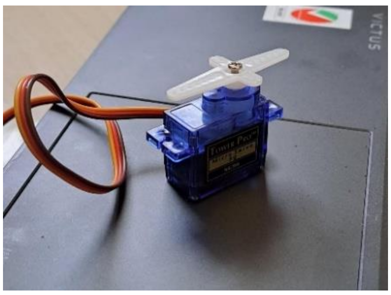

Figure 1.12

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Chapter 9

Smart Sleep Apnea Monitoring Device

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Abstract

Sleep apnea is a serious sleep disorder in which breathing repeatedly stops and starts again. The risk factors include age and obesity. The sleep disorder is associated with a medical disorder where the normal sleeping pattern of the person is disturbed. The common sleep disorder is sleep apnea. Sleep apnea has different types. Obstructive sleep apnea is the most common form that occurs when throat muscles relax, whereas Central sleep apnea occurs when the brain doesn't send proper signals to the muscles that control breathing. About 1 billion people worldwide suffer from sleep apnea disorder, and the age group of above 40 years old is affected by this disorder. Sleep apnea symptoms are loud snoring, morning headache, irritability, and gasping for air during sleep. It rarely occurs in men for 20-44years old and mostly affects in men for 45-64 years old. The existing sleep apnea devices are costly and not very user-friendly. The proposed proposal is designed to monitor heart rate detection. It is very comfortable for patients, and the design is compact and can be used for infants, as well as the graphical output can be continuously monitored through a computer screen or LCD.

Keywords: Sleep apnea; snoring; sleeping disorders; breathing; heart rate monitor

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1. Introduction

Sleep disorder is associated with a medical disorder where the normal sleeping pattern of the person is disturbed. Some sleeping disorders may lead to serious problems in physical, mental, social health. Some of the common types of sleep disorders are sleep apnea, narcolepsy, jetlag, sleepwalking, Sleep paralysis. The general factors that cause sleep disorders are physical, mental and environment and psychiatric problems and other factors such as genetics, night shift duty, Medicines and aging. Sleep apnea types are Obstructive sleep apnea, the more common form that occurs when throat muscles relax. Central sleep apnea, which occurs when your brain doesn't send proper signals to the muscles that control breathing about 1 billion people suffer from sleep apnea disorder and above 40 age is affected for this sleep apnea disorders. Sleep apnea symptoms are loud snoring, morning headache, irritability, gasping for air during sleep. The risk factors are acute stroke, neurological problems, congestive heart failure etc. This sleep apnea disorder may be lethal if it is untreated. prevalence of obstructive sleep apnea disorder is 2.4% to 4.96% in men and 1% to 2% in women in the Indian subcontinent.

2. LITERATURE SURVEY

A. Christian Rotariu, et.al (2016) designed continuous respiratory monitoring device for detection of sleep apnea episodes. In this proposed device architecture includes piezoelectric thoracic belt attached to the patient's chest and used to measure respiratory signal. Signal conditioning contains op-amp and it contain arduino atmega 32. Tablet pc is used to display the signal [1]

B. Santhoshini Arulvallal, et.al (2019) design and development of wearable device for continuous monitoring of sleep apnea disorder. In this paper they could detect heart rate, spo2 sensors are connected to arduino. Liquid crystal screen is used to show these parameters. Measure parameters are transferred from the device to smart phone through Bluetooth [2].

C. Hongxu Zhu1,et.al(2018) development of Sleep apnea monitoring for smart health care .In this paper a new classifier designed for sleep stage classification among awake , light sleep , deep sleep .A new kernel is designed is used for sleep apnea classification .In this paper new support vector machine proposed for sleep apnea assessment .They find the average distribution of sleep stages for normal people and sleep apnea patients and they mainly take two

3. **METHODOLOGY**

The proposed method has been designed for detection of sleep apnea continuously. The proposed proposal has to monitor heart rate and respiration rate using accelerometer sensor. It is very comfortable for patients and the design is compact and can be used for infants as well as the graphical output can be continuously monitored through a computer screen or LCD display.

3. Block Diagram

The working methodology of smart sleep apnea monitoring device was explained in the block diagram. The heart rate and respiration values were obtained from the subjects using ky052 and sensor respectively. The microcontroller Arduino UNO is programmed to display the values of the parameters such as heart rate, respiration rate and accelerometer sensor rate in the personal computer.

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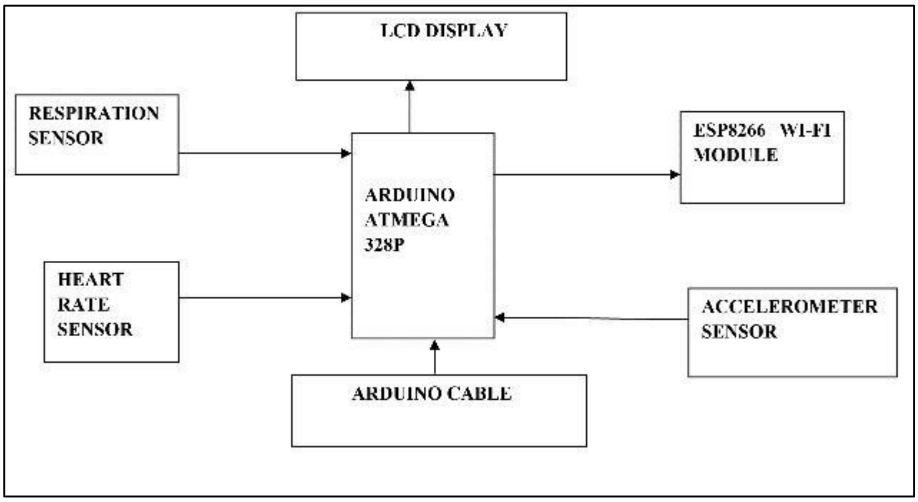

Fig.1. Block diagram

Arduino

Arduino is a single-board microcontroller to make using electronics in multidisciplinary projects more accessible. The hardware consists of a simple open-source hardware board designed around an 8-bit Atmel AVR microcontroller, or a 32-bit Atmel ARM. The software consists of a standard programming language compiler and a booloader that executes on the microcontroller

Microcontroller ATmega328 has operating voltage of 5V, its recommended input voltage is 7-12V, input voltage limits are 620V, flash memory is 32 KB, SRAM is 2KB, clock speed is 16MHz.

Heart Rate Sensor: Ky05

The sensor is made to shine an infrared led through your finger. The infrared sensor on the other side can then pick up slight changes in the light transmittance through your finger when blood is pumped in. When the sensor senses light, it becomes more resistant, causing the voltage reading in the serial monitor to go down. However, if your sensor is anything like mine, the LED is not bright enough to be detected by the sensor even when nothing is obstructing it, so the sensor constantly reads 5v. I tried replacing the LED with a stronger one and got slightly better results, but I don't think the sensor itself is sensitive enough to be able to detect a heartbeat over random noise and movements. The sensor is a simple 3-pinned analog sensor. Plug the ground in the -, the 5v to the middle pin and A0 to the S pin.

Accelerometer Sensor:GY521

Accelerometer sensor is used for motion processing in sleeping time. Internal Digital Motion Processing™ (DMP™) engine supports 3D Motion Processing and gesture recognition algorithms. The MPU-60X0 collects gyroscope and accelerometer data while synchronizing data sampling at a user defined rate. The total dataset obtained by the MPU-60X0 includes 3-Axis gyroscope data, 3Axis accelerometer data, and temperature data. The MPU's calculated output to the system processor can also include heading data from a digital 3-axis third party magnetometer. The FIFO buffers the complete data set, reducing timing requirements on the system processor by allowing the processor burst read the FIFO data. After burst reading the FIFO data, the system processor can save power by entering a low-power sleep mode while the MPU collects more data

Respiration Sensor: LM358

LM358 is a dual op-amp IC integrated with two op-amps powered by a common power supply. It can be considered as one half of LM324 Quad op-amp which contains four op-amps with common power supply. The differential input voltage range can be equal to that of power supply voltage. The typical supply current is 500uA independent of the supply voltage range and a maximum current of 700uA. The operating temperature ranges from 0˚C to 70˚C

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Esp8266 Wi-Fi Module:

ESP8266 is Wi-Fi enabled system on chip (SoC) module developed by Es press if system. It is mostly used for development of IoT (Internet of Things) embedded applications.

6. RESULT AND DISCUSSION

The device was tested with the volunteers (normal subjects) and acquired the relevant parameters. The relevant parameters observed more or less meet the accuracy of the same parameters (with normal value) obtained through the polysomnography method. The following tabulation shows the parameters obtained through the test conducted.

S.No	Sub	Gender	Age	Respiration Rate	Heart Rate	Sleeping Disturb
1	Sub1	Male	49	21	78	5
2	Sub2	female	42	30	79	2
3	Sub3	male	24	10	78	0
4	Sub4	male	47	21	74	5
5	Sub5	female	42	10	78	0
6	Sub6	male	57	9	76	8
7	Sub7	female	29	14	85	1
8	Sub8	male	46	18	79	2
9	Sub9	female	35	15	85	0
10	Sub10	male	25	9	76	0

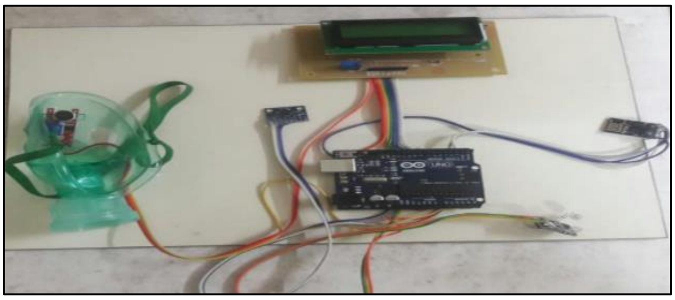

Fig.2. Experimental Setup of Sleep Apnea Monitoring Device

6. SUMMARY AND CONCLUSION

In this proposed study, smart sleep apnea monitoring device was developed which can measure respiration rate, heart rate and movement detection using accelerometer sensor by real time. This monitoring device overcomes the complexities of the other commonly used portable sleep apnea device. The observational values obtained through the device shows high compactness with polysomnography results. This brought the capability of sleep apnea monitoring is a cost-effective, power-efficient manner. The developed device extents the screening capacity of sleep apnea syndrome which can be used for the further treatment process. Sleep apnea monitoring device is portable and designed to be the wearable for continuous monitoring of patients. The parameters such as heart rate, respiration rate and movement detection during sleeping using accelerometer sensor. As a future work, we include CPAP parameter obtained from the prototype device will be transferred to the smart phone by Bluetooth/Wi-Fi using the Wi-Fi module for the further analysis.

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Chapter 10

Green Alternatives in Fiber-Reinforced Concrete: A Future-Ready Approach

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Abstract

Fiber-Reinforced Concrete (FRC) represents a major innovation in construction materials, offering substantial improvements in strength, durability and sustainability over conventional concrete. This review provides a comprehensive analysis of recent advancements in the use of fibers in concrete, with a focus on optimizing its mechanical and structural properties. It examines the impact of different fiber types, volume fractions and distribution methods on crack resistance, load-bearing capacity and long-term performance. The review also explores contemporary trends, such as the use of hybrid fibers, natural and recycled fibers and nanofibers, and discusses the challenges and research gaps in the field.

Keywords: Durability enhancement, Hybrid fiber systems, Construction materials optimization, Hybrid fiber systems

1. Introduction

Concrete is the most extensively used construction material worldwide, appreciated for its cost-effectiveness, ease of availability, and adaptability to a wide range of construction needs. From residential buildings to massive infrastructure projects, concrete

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serves as the backbone of modern civil engineering. Despite its numerous advantages, conventional concrete exhibits significant limitations, especially under tensile stress. One of the primary shortcomings of traditional concrete is its inherent brittleness and low tensile strength, which makes it highly susceptible to cracking and structural failure, particularly under dynamic or cyclic loading conditions. These cracks, though initially microscopic, can propagate over time, compromising the long-term durability and safety of structures. In high-performance applications such as bridges, tunnels, industrial floors, and earthquake-resistant buildings, this limitation becomes critically important. Among them, fiber reinforcement has emerged as a promising and versatile solution. When fibers are uniformly distributed within the concrete matrix, they act as crack arrestors and bridge micro-cracks, significantly enhancing the ductility, impact resistance, and post-cracking behavior of the material. This fiber inclusion leads to a composite material known as Fiber-Reinforced Concrete (FRC).

2. Types of Fibers Used in Concrete

The selection of fiber type significantly influences the mechanical behavior, durability, and application suitability of Fiber-Reinforced Concrete. Each fiber material contributes unique characteristics to the composite matrix. The most commonly used fibers include steel, synthetic, natural, basalt, and glass fibers. Below is a structured overview and expanded explanation of each:

2.1 Steel Fibers

2.1.1 Overview : Steel fibers are among the most widely used and researched materials in FRC due to their excellent mechanical properties.

2.1.2 Key Benefits:

Enhanced Tensile and Flexural Strength: Steel fibers significantly increase the tensile and flexural strength of concrete, making it more ductile and resistant to cracking under load.

Impact and Fatigue Resistance: They improve the concrete’s ability to absorb energy and resist repeated loading cycles, which is crucial for industrial flooring and highway pavements.

Post-Cracking Behavior: Steel fibers help bridge cracks after they form, enhancing the load-carrying capacity of concrete even in a cracked state.

2.1.3 Typical Applications:

Airport runways

Industrial floors and pavements

Tunnel linings and precast segments

2.2 Synthetic Fibers

2.2.1 Overview: Synthetic fibers such as polypropylene, nylon, and polyethylene are commonly added to concrete for improved performance during both plastic and hardened states.

2.2.2. Key Benefits: Shrinkage Crack Reduction: Synthetic fibers reduce plastic shrinkage and thermal cracking, especially during the early curing stages.

Improved Durability: These fibers increase resistance to freeze-thaw cycles, abrasion, and chemical attack.

Corrosion Resistance: Unlike steel, synthetic fibers do not corrode, making them suitable for chemically aggressive environments.

2.2.3 Typical Applications: Residential slabs and overlays

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Shotcrete applications

Repair mortars and lightweight panels

2.3 Natural Fibers

2.3.1Overview: Natural fibers such as jute, coir, sisal, flax, and hemp are biodegradable and renewable, offering a sustainable alternative to synthetic and metallic fibers.

2.3.2 Key Benefits: Eco-Friendly: Derived from agricultural by-products, these fibers contribute to sustainable construction.

Improved Crack Resistance: Natural fibers effectively control crack propagation and enhance tensile toughness.

Low Cost and Readily Available: Especially in developing countries where agricultural waste can be repurposed.

2.3.3 Challenges: Variability in Performance: Due to their organic nature, natural fibers may degrade in alkaline environments and vary in quality.

Moisture Absorption: High water absorption can affect the workability and long-term durability of concrete.

2.3.4 Typical Applications:

Rural infrastructure

Low-cost housing

Non-structural architectural elements

2.4 Basalt Fibers

2.4.1Overview: Basalt fibers are made from volcanic basalt rocks and are gaining attention for their excellent strength, durability, and resistance properties.

2.4.2 Key Benefits: High Tensile Strength and Modulus: Basalt fibers improve the mechanical integrity of concrete under load.

Corrosion and Chemical Resistance: Suitable for harsh, marine, or corrosive environments.

Cost-Effective: Offers a balance between performance and affordability compared to carbon fibers.

2.4.3 Typical Applications:

Marine and offshore structures

Bridge decks and retaining walls

Fire-resistant construction

2.5 Glass Fibers

2.5.1Overview: Glass fibers, particularly alkali-resistant (AR) glass, are used to reinforce concrete in both architectural and structural applications.

2.5.2 Key Benefits: Excellent Chemical and Water Resistance: Ideal for use in marine and chemically exposed environments.

Lightweight and High Tensile Strength: Adds strength without significantly increasing the weight of the concrete.

Improved Aesthetics: Often used in decorative or thin-walled elements due to their fine texture.

2.5.3 Challenges: Alkali Sensitivity: Ordinary glass fibers can degrade in the highly alkaline environment of concrete unless treated or AR-grade is used.

2.5.4 Typical Applications:

Architectural cladding panels

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Precast façade elements

Marine infrastructure

3. Performance Enhancements Through Fiber Optimization

3.1 Mechanical Properties of Fiber-Reinforced Concrete

Fibers significantly enhance the mechanical performance of concrete by improving its compressive, tensile, and flexural strength. This improvement is primarily due to the fibers ability to bridge micro-cracks and redistribute stress across the matrix, which delays the onset of macro-cracks and structural failure.

Compressive Strength: While fibers have a limited effect on compressive strength compared to tensile or flexural strength, certain types like steel and basalt can slightly increase it by confining the concrete matrix.

Tensile Strength: Fibers increase the tensile strength by providing bridging action that holds the matrix together under tension, especially important in applications like slabs, pavements, and precast elements.

Flexural Strength: The most significant benefit is observed in flexural strength, where fibers reduce crack propagation under bending loads, enhancing the concrete’s load-bearing capacity.

The degree of improvement in mechanical properties depends on several key factors:

Type of fiber (e.g., steel, glass, polypropylene, basalt)

Aspect ratio (length to diameter ratio of the fiber)

Volume fraction (the percentage of fiber by volume in the concrete mix)

Bonding characteristics between the fiber and the cement matrix

3.2 Durability Enhancement with Fibers

Fibers contribute substantially to the durability of concrete, making it more resistant to harsh environmental conditions and chemical exposures.

Reduced Permeability: Fibers help block the formation of continuous capillary channels, which lowers the permeability of concrete. This minimizes the ingress of water and harmful agents like chlorides and sulfates.

Chemical and Chloride Attack Resistance: The inclusion of certain fibers, such as basalt and steel, improves the concrete's resistance to chemical corrosion and chloride ingress, especially important in coastal, industrial, and dicing environments.

Among various fiber types, basalt and steel fibers are particularly noted for their exceptional resistance in chemically aggressive and high-moisture environments due to their high strength, corrosion resistance, and thermal stability.

3.3 Crack Mitigation and Control

One of the most valuable advantages of using fibers in concrete is their ability to mitigate cracks and improve structural integrity over time.

Delay in Crack Initiation and Propagation: Fibers intercept the development of micro-cracks and slow down their growth, thereby delaying the formation of larger, structural cracks.

Reduction in Crack Width: When cracks do form, fibers help control their width by bridging across them. This minimizes visual

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deterioration and improves the appearance and performance of the concrete surface.

Enhanced Structural Integrity and Service Life: By limiting crack development and controlling crack width, fibers maintain the concrete's load-bearing capacity, reduce the risk of corrosion in embedded steel reinforcement, and extend the structure’s service life.

4. Challenges In Fiber-Reinforced Concrete

Fiber Dispersion and Orientation: Achieving uniform fiber dispersion and orientation is critical for optimal performance. Poor distribution can lead to uneven mechanical properties and compromised durability.

5. Emerging Trends and Future Directions

Hybrid Fiber Systems Combining different fiber types can synergistically enhance concrete performance. For example, steel fibers can provide strength, while synthetic fibers enhance durability and shrinkage resistance.

6. Conclusion

Fiber-reinforced concrete (FRC) represents a transformative innovation in construction materials, offering enhanced performance compared to conventional concrete. By optimizing key factors—such as fiber type, volume fraction, and distribution—significant improvements in mechanical properties and durability can be achieved. These enhancements make FRC particularly suitable for demanding applications requiring high strength, toughness, and crack resistance. However, the adoption of FRC is not without challenges. Issues such as increased cost, reduced workability, and difficulty in uniform fiber dispersion can hinder its widespread use.

To address these concerns, ongoing research is focusing on innovative solutions, including hybrid fiber systems (combining different fiber types for synergistic effects), nano-modified fibers (incorporating nanomaterials to enhance performance), and sustainable alternatives (such as natural or recycled fibers).Looking ahead, future studies should aim to overcome existing limitations while exploring novel applications of fiber-reinforced concrete—especially in areas such as 3D printing, smart infrastructure, and sustainable construction. With continued innovation, FRC holds immense potential to shape the next generation of high-performance, resilient, and eco-friendly building materials.

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Chapter 11

The Third Space in Transit: Hybridity in Memories of Rain and a Sin of Colour

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Abstract

This paper explores the representation of hybridity in Sunetra Gupta's Memories of Rain (1992) and A Sin of Colour (1999), two novels that negotiate cultural crossings, diasporic dislocations, and fragmented identities. Drawing upon Homi K. Bhabha's theory of the "Third Space" and other postcolonial perspectives, it examines how Gupta's protagonists navigate multiple cultural, linguistic, and emotional geographies between India and England. Both novels depict characters whose lives are suspended between homeland and adopted land, memory and reality, belonging and estrangement. Through her poetic prose, non-linear narrative structures, and layering of time and space, Gupta creates a literary form that mirrors the hybrid consciousness of her characters. This study argues that hybridity in Gupta's fiction is not merely a symptom of displacement but a creative and destabilizing force that reshapes identity while simultaneously producing a deep sense of alienation. By comparing the narrative strategies and thematic resonances of the two novels,

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the paper situates Gupta's work within the larger discourse of postcolonial and diasporic literature.

Keywords: Sunetra Gupta; hybridity; postcolonial fiction; Memories of Rain; A Sin of Colour; Third Space;

1. Introduction

In the field of contemporary Indian English fiction, Sunetra Gupta holds a distinctive place as a novelist whose work bridges art and science, linguistic precision and lyrical beauty. Born in Calcutta and educated in various parts of the world, including Zambia and the United Kingdom, Gupta herself embodies a transnational identity, a lived experience that deeply informs her fiction. Her novels often explore the complex terrain of displacement, memory, and the interplay between cultural identities.

Two of her most acclaimed works, Memories of Rain (1992) and A Sin of Colour (1999), stand as compelling explorations of what postcolonial theorists term "hybridity." In Homi K. Bhabha's influential conception, hybridity emerges in the "Third Space" — a liminal zone where cultures intersect and where fixed notions of identity are unsettled. This hybridity is not merely a fusion of elements; it is a dynamic, often uneasy negotiation that produces new meanings and subjectivities.

In both Memories of Rain and A Sin of Colour, Gupta constructs narratives that move between Calcutta and England, the colonial past and the postcolonial present, interior landscapes and external geographies. Her characters are caught in multiple currents: personal passion and moral duty, nostalgic attachment and pragmatic adaptation, linguistic fluency and cultural estrangement. The hybridity in these novels operates not only at the thematic level but also through formal innovation—fragmented chronology, lyrical language, and overlapping narrative voices.

This paper investigates how hybridity functions in these two novels as both an identity condition and a narrative strategy. It argues that Gupta's fiction enacts hybridity as an aesthetic, structural, and psychological phenomenon, thereby challenging simplistic binaries of home and abroad, self and other.

1.1 Theoretical Framework: Hybridity and the Third Space

The concept of hybridity has been central to postcolonial studies, particularly since Homi K. Bhabha's The Location of Culture (1994). For Bhabha, hybridity emerges in the interstitial spaces between cultures, where negotiation produces new identities and meanings. This "Third Space" destabilizes essentialist notions of culture, revealing identity to be contingent, fluid, and performative.

Avtar Brah's notion of "diaspora space" similarly emphasizes the intersection of multiple subject positions—gender, race, class, nationality—within the migrant's lived reality. Stuart Hall extends this idea by arguing that cultural identity is not a fixed essence but a "production," always in process, shaped by historical and social contexts.

2. Applied to Gupta's novels, these theories highlight the multiple axes of hybridity her characters inhabit:

2.1 Cultural Hybridity: Navigating Indian and British Cultural Codes

Cultural hybridity in Gupta's novels operates as a negotiation between the customs, values, and social etiquettes of Indian and British life. In Memories of Rain, Moni enters an English domestic space already carrying the affective and ritual sensibilities of her

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Bengali upbringing—family intimacy, emotional expressiveness, and ceremonial warmth. In Britain, she encounters a culture marked by reserve, individualism, and subtle social codes that differ sharply from the communal structures of her childhood. Her life becomes a continuous act of translation—how to host a dinner, interpret conversational silences, or read her husband's emotional distance—each shaped by cultural frameworks alien to her own.

In A Sin of Colour, Debendranath navigates two contrasting codes: the moral imperatives of his Bengali heritage (loyalty to family, adherence to unspoken social obligations) and the intellectual and personal freedoms encouraged in Oxford's academic environment. His identity exists in a constant state of cultural negotiation—embracing certain aspects of English life while retaining deep emotional allegiance to Indian familial structures. This mirrors Homi Bhabha's observation that cultural hybridity "revalues the past, reconfigures the present, and opens up the possibility of alternative cultural futures."

2.2 Linguistic Hybridity: Shifting Between Thought-Worlds Shaped by Different Languages and Literary Traditions

Linguistic hybridity in Gupta's fiction is not simply a matter of using multiple languages; it is about inhabiting different thought-worlds. In Memories of Rain, Moni's consciousness is steeped in the rhythms of Bengali speech and literary memory, even when her narrative voice is in English. Her thoughts often carry the sensory density of Bengali idioms—seasonal metaphors, domestic images, the emotional lexicon of her mother tongue. Simultaneously, her mind is shaped by English literary traditions, especially romantic poetry, which frames her initial idealization of England. This results in a hybrid mental register: her interior world is bilingual even when the text appears monolingual.

In A Sin of Colour, Debendranath's Oxford life is marked by the precision of academic English discourse, yet his memories of Calcutta return in a different linguistic register, thick with familial nicknames, colloquial Bengali, and the texture of oral storytelling. Gupta's prose mirrors this hybridity—her sentences often shift between the sparse clarity of English narrative and the lyrical layering reminiscent of Bengali narrative cadence. This interplay enacts what Mikhail Bakhtin would call a heteroglossia of consciousness, where multiple speech patterns and cultural references coexist in the same narrative fabric.

2.3 Spatial Hybridity: Existing Between Geographically and Emotionally Distant Worlds

Spatial hybridity in Gupta's novels is not just about physical location but about the emotional geographies her characters inhabit. Moni in Memories of Rain lives in London but emotionally resides in Calcutta; her memories of monsoon rains, crowded streets, and familial kitchens constantly intrude upon her experience of the cold, orderly English landscape. This creates a doubled sense of space—she is never fully in one place because another is always layered beneath it.

Similarly, Debendranath in A Sin of Colour inhabits two worlds: the decaying ancestral home of Mandalay in Calcutta and the serene waterways of Oxford. These spaces are deeply symbolic: Calcutta represents rootedness, inheritance, and unresolved emotional ties; Oxford stands for detachment, reinvention, and a curated intellectual identity. The narrative moves fluidly between these spaces, showing how diasporic consciousness often exists in overlapping

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cartographies—what Avtar Brah calls diaspora space, where home and abroad are not opposites but coexisting frames of reference.

3. Narrative Hybridity: Blending Temporalities, Genres, and Forms

Gupta's narrative structures themselves embody hybridity. In Memories of Rain, the stream-of-consciousness technique merges past and present without chronological order, collapsing decades into moments of recollection. The text reads like a fusion of lyrical prose and dramatic monologue, incorporating intertextual references to English poetry alongside sensory evocations of Bengali life. This blending of genres—romantic poetry, psychological novel, modernist stream-of-consciousness—creates a narrative form that refuses singular classification.

In A Sin of Colour, the narrative hybridity is evident in its multi-perspectival storytelling, where memories, letters, and shifting narrators create a mosaic-like narrative. Time is non-linear, fragmented into episodes that readers must piece together, echoing the fractured nature of diasporic identity. Gupta merges realist family saga with modernist experimentation, weaving together intimate love story, gothic family mystery, and meditative reflections on exile. Such hybridity of form mirrors the thematic hybridity of identity, enacting in structure what the characters live in experience.

Gupta's narrative worlds are thus not simple portraits of migration or nostalgia; they are textured spaces where identity is continually negotiated and never fully resolved.

4. Hybridity in Memories of Rain

Published in 1992, Memories of Rain tells the story of Moni, a young Bengali woman who marries Anthony, an Englishman, and moves to

London. Her journey begins with a romanticized vision of England, shaped by her colonial education and readings of English literature. England, in her imagination, is a "demi-paradise" — a landscape of refinement and poetic charm. Yet the reality she encounters is starkly different: emotional coldness, marital infidelity, and cultural alienation.

4.1 Cultural Hybridity and Disillusionment

Moni's experience reflects the clash between imagined cultural ideals and lived realities. Her Bengali upbringing, steeped in familial intimacy and sensory richness, contrasts sharply with the restrained, often isolating environment of England. The hybridity here is double-edged: it offers Moni access to new experiences but also exposes her to dislocation. Her identity becomes a site of negotiation between the warmth of her remembered Calcutta and the cold precision of London life.

4.2 Linguistic and Intertextual Hybridity

Gupta's prose mirrors Moni's hybrid consciousness. The novel blends English idioms with rhythms suggestive of Bengali speech, producing a style that is neither fully one nor the other. Intertextual references to English poetry coexist with sensory descriptions of Bengali domestic life, creating a layered linguistic space.

4.3 Narrative Hybridity

The novel employs a stream-of-consciousness technique that merges past and present, dream and reality. Moni's memories of monsoon rains in Calcutta intrude upon her perception of London streets, collapsing temporal and spatial boundaries. The narrative's cyclical structure—where memories constantly return—embodies the hybrid condition of living in two places at once.

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4.4 Hybridity as Emotional Displacement

While hybridity can be enabling, in Moni's case it becomes a source of emotional fragmentation. She belongs to neither culture entirely and is estranged even within her own marriage. Gupta thus presents hybridity as a lived paradox—rich in potential but fraught with instability.

5. Hybridity in a Sin of Colour

A Sin of Colour (1999) continues Gupta's engagement with hybridity but through a different lens. Here, the protagonist Debendranath Roy leaves Calcutta for Oxford after falling in love with his brother's wife, Reba. His exile is both a moral escape and a journey into another cultural sphere.

5.1 Spatial Hybridity

The novel alternates between the decaying mansion of Mandalay in Calcutta and the serene waterscapes of Oxford. These spaces are not mere settings; they are symbolic geographies of the protagonist's divided self. Oxford represents intellectual freedom and emotional distance; Calcutta embodies familial entanglements and sensory intensity.

5.2 Temporal Hybridity

Time in A Sin of Colour is non-linear, fractured into memories, letters, and intersecting narratives. Past and present flow into each other, suggesting that exile never severs the ties of memory. This temporal hybridity reflects the way diasporic identities are constructed—always in dialogue with a remembered past and an unfolding present.

5.3 Psychological Hybridity

Debendranath's identity is shaped by the codes of two cultures: the moral obligations of his Bengali heritage and the individualistic ethos of his English surroundings. His life in Oxford is haunted by recollections of Calcutta, producing a hybrid selfhood suspended between longing and adaptation.

5.4 Linguistic and Imagistic Hybridity

Gupta's prose in this novel often blends Indian and European imagery within a single description. The sensory evocation of mango trees in Calcutta might be juxtaposed with the crispness of an Oxford morning, collapsing spatial divides in the reader's imagination.

6. Comparative Discussion: Hybridity in Memories of Rain and A Sin of Colour

Sunetra Gupta's Memories of Rain (1992) and A Sin of Colour (1999) both take hybridity as a central imaginative concern, but the texture, emotional register, and narrative framing of that hybridity differ markedly. Both novels feature protagonists suspended between India and England, inhabiting a liminal zone where identity is neither fixed nor singular. Yet while Memories of Rain foregrounds marital and cultural disillusionment, A Sin of Colour places hybridity within a larger meditation on exile, inheritance, and the hauntings of memory.

6.1 Emotional vs. Spatial Hybridity

In Memories of Rain, hybridity emerges as an emotional fracture. Moni enters her marriage with an Anglo-Indian romantic idealism nourished by both Bengali sensibility and the English literary canon. Her consciousness is steeped in Tagore and Tennyson, the monsoon of Calcutta and the drizzle of England, and she expects these worlds

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to merge seamlessly within the marital home. Instead, the marriage becomes a crucible of alienation. The foreignness of her husband's cultural world is not exotic but exclusionary; her Bengali identity becomes an object of subtle othering. The novel's relentless interior monologue reflects this claustrophobia—readers remain inside Moni's thoughts, where the rain of memory continually blurs the line between her Indian past and her English present. Hybridity here is lived as an unbearable simultaneity, a psychological double exposure where neither cultural image achieves clarity.

By contrast, A Sin of Colour refracts hybridity through the prism of geographic and mnemonic displacement. Debendranath's life oscillates between Oxford and the crumbling Calcutta estate of Mandalay. England is not simply an alienating present; it is a self-chosen space of exile that both shelters and estranges him. Calcutta exists as an emotional homeland but is accessible only through the distorted lens of memory. Here hybridity is not confined to a marriage but is woven into the protagonist's entire life geography—his identity is a shifting palimpsest written over by the traces of both spaces.

6.2 Theoretical Frames: Hybridity as Negotiation

In postcolonial theory, Homi Bhabha's notion of the "Third Space" describes hybridity as a site of cultural negotiation, where identity is constructed through the interplay of difference rather than the resolution of it. Moni and Debendranath inhabit this third space, but their negotiations differ:

- Moni negotiates between romanticised Englishness and the lived reality of racialised womanhood in Britain, between the internalised voice of English literature and the inherited rhythms of Bengali speech and thought. Her hybridity is an affective battleground.

- Debendranath negotiates between the demands of familial legacy and the pull of self-imposed exile, between the spatial immediacy of Oxford and the temporal distance of Calcutta as remembered. His hybridity is a temporal and geographic oscillation.

Stuart Hall's conception of identity as "becoming as well as being" is especially relevant: in both novels, hybridity is not a stable possession but an ongoing process. The characters are perpetually "in formation," their identities never fully consolidated.

6.3 Linguistic and Cultural Hybridity

Both novels employ linguistic hybridity to dramatise this negotiation. In Memories of Rain, the English prose is laced with Bengali idioms, cadences, and imagery, producing what Gayatri Spivak calls a "translational consciousness"—writing that thinks in one language while speaking in another. This reproduces Moni's own mental state, shifting between the "thought-worlds" of two literary and cultural traditions. In A Sin of Colour, linguistic hybridity works more subtly. Debendranath's English is polished and intellectual, yet the novel's descriptions of Calcutta are infused with sensory detail and associative memory that betray an Indian narrative gaze. Gupta's sentences slide between these modes without explicit transition, reflecting the fluidity—and sometimes instability—of hybrid thought.

6.4 Narrative Hybridity

Gupta's formal strategies themselves enact hybridity. In Memories of Rain, the narrative is almost entirely interior, with a looping temporal structure that refuses linear progression. The novel blends the

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lyricism of Bengali poetry with the stream-of-consciousness style of modernist English fiction, producing a hybrid narrative form that mirrors Moni's fractured identity.

A Sin of Colour adopts a multi-perspectival approach, moving between voices, times, and places. Here the hybridity is not only in the characters' identities but in the novel's architecture: the narrative accommodates both the personal immediacy of memory and the detached objectivity of third-person narration. The temporal layering—past and present folding into each other—creates a structural analogue to the in-betweenness of hybrid identity.

6.5 Unresolved Endings

Perhaps the most striking similarity between the novels is Gupta's refusal to resolve hybridity into a final synthesis. Neither Moni nor Debendranath arrives at a fixed identity. Instead, they remain in perpetual negotiation—Moni between disillusionment and the pull of memory, Debendranath between exile and the imagined return. This aligns with Avtar Brah's notion of "diaspora space" as an ongoing, contested terrain rather than a destination.

In Memories of Rain, hybridity leaves the protagonist emotionally stranded; in A Sin of Colour, it renders the protagonist permanently itinerant in spirit, even when physically settled. In both cases, hybridity is less a "solution" than a condition of being—mutable, unstable, and deeply human.

7. Conclusion

Sunetra Gupta's *Memories of Rain* and *A Sin of Colour* portray hybridity as a multi-layered and dynamic phenomenon, encompassing cultural, linguistic, spatial, temporal, and psychological dimensions. In both novels, the protagonists inhabit what Homi K. Bhabha terms the “Third Space”—a liminal zone where identity is neither fixed nor singular but continually renegotiated in response to shifting contexts. This space is not merely geographic but also emotional and intellectual, a site where inherited traditions, acquired sensibilities, and lived realities intersect in complex, often conflicting ways.

Gupta’s narrative strategies actively embody hybridity rather than simply representing it. Her use of non-linear structures disrupts chronological expectations, allowing past and present to coexist in a fluid interplay that mirrors the protagonists’ in-between identities. The lyrical quality of her prose, infused with sensorial detail and shifting narrative rhythms, draws from both Bengali literary aesthetics and the modernist experimentation of English fiction. Furthermore, her intertextual layering—allusions to both Western and Indian literary canons—creates a textual hybridity that mirrors the mental landscapes of her characters, whose thought worlds are shaped by multiple cultural references.

By deliberately resisting neat narrative resolutions, Gupta reflects the lived reality of diasporic existence. Hybridity, in her fiction, is not a harmonious fusion that erases differences; instead, it is a perpetual negotiation, an ongoing process of becoming. It offers moments of creative possibility, where new identities and perspectives can emerge, but it is equally marked by emotional tension, alienation, and longing. This refusal to stabilise identity into a final synthesis challenges romanticised notions of cultural blending and acknowledges the often-uneasy work of living across worlds.

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Through these strategies, Gupta's work makes a significant contribution to postcolonial literature's understanding of transnational subjectivity. She shows how hybrid identities are not only lived in everyday interactions but also imagined in memory and constructed through narrative form. Her fiction thus stands as both a literary enactment and a critical exploration of hybridity, situating her among contemporary writers who capture the nuanced textures of global, migratory life.

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Chapter 12

Cutting Through Silence: A Socio-Literary Study of Bama's Karukku

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Abstract

Bama's Karukku (1992) stands as a milestone in Indian Dalit literature, breaking new ground as one of the first autobiographies written by a Dalit woman in Tamil. Through an unflinching narrative voice, Bama exposes the intertwined oppressions of caste, gender, and religion, drawing upon her lived experiences as a Catholic Dalit woman in rural Tamil Nadu. The text disrupts conventional literary forms, blending autobiography with oral storytelling and testimonial writing. This article examines Karukku through multiple lenses: the socio-political context of Dalit life, the thematic focus on resistance and self-assertion, the intersection of caste and religion, the deployment of oral narrative techniques, and the articulation of a distinct Dalit feminist perspective. It situates the text within the broader framework of subaltern studies and postcolonial theory, emphasizing Bama's challenge to dominant cultural narratives. In doing so, the article highlights how Karukku functions simultaneously as a personal testimony and a collective voice for the

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marginalized, redefining Indian autobiographical writing in both form and purpose.

Keywords: Bama; Karukku; Dalit literature; Tamil autobiography; caste oppression; Dalit feminism;

1. Introduction

When Karukku first appeared in 1992, it marked a radical departure from anything the Tamil literary world had encountered before. Authored by Bama Faustina Soosairaj—a Catholic Dalit woman—this text broke through multiple, interlocking silences: the silence imposed by an oppressive caste order, the silence sustained by the Catholic Church's complicity in caste discrimination, and the almost total absence of Dalit women's voices in the public literary sphere. In bringing her voice to print, Bama challenged not only the institutions that perpetuated injustice but also the aesthetic norms of Tamil literature, which had long been dominated by upper-caste perspectives and elite linguistic registers.

The Tamil title Karukku—literally referring to the double-edged, serrated leaves of the palmyra tree—functions as a resonant metaphor throughout the work. Its dual sharpness captures the paradox of the Dalit condition: on one side, the lacerations of systemic oppression; on the other, the piercing power of truth-telling and resistance. This symbolic layering signals that Bama's narrative is not merely an act of remembrance but also a deliberate intervention—an attempt to cut through complacency and force the reader to confront uncomfortable realities. Structurally, Karukku rejects the linearity of conventional autobiography. Instead, it unfolds through a series of recollections, meditations, and sharply etched vignettes that move fluidly across time, reflecting the cyclical and associative nature of memory. This narrative strategy closely mirrors the oral storytelling traditions of her community, where stories are not bound by chronological order but by thematic resonance and emotional urgency. Bama's decision to write in a Tamil deeply inflected by the rhythms, idioms, and syntax of rural Dalit speech is itself a political act. It resists the polished, Sanskritized Tamil favored by literary elites, foregrounding the politics of language and insisting that the lived realities of Dalits can only be authentically articulated in their own linguistic register.

Bama's personal journey—traced from her childhood in a small Tamil village, through her years of education and her eventual entry into a Catholic convent—serves as the spine of the text. Yet Karukku never collapses into a purely individual memoir. Every personal episode is inextricably bound to the broader social structures that enable exclusion, reinforce caste hierarchies, and constrain agency. The account of her disillusionment with religious life, for example, is not framed as a crisis of individual faith alone, but as an exposure of the systemic contradictions between the Church's proclaimed universalism and its everyday perpetuation of caste-based segregation.

In this way, Karukku operates on two levels simultaneously: it is both a deeply personal narrative of awakening and a searing collective indictment of entrenched social injustices. By fusing autobiography with manifesto, Bama reframes life writing as a site of resistance—an embodied archive of struggle, survival, and defiance.

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2. Socio-Political Context

2.1 Dalit Life in Tamil Nadu

Dalits in Tamil Nadu, historically referred to as "Paraiyars" and "Pallars," have long been subject to systemic oppression—socially ostracized, economically exploited, and ritually degraded. Even after the abolition of untouchability by the Indian Constitution, caste hierarchies persist, often in subtler yet equally violent forms. Access to education, employment, and land ownership remains limited.

Bama's childhood memories vividly capture these inequities: Dalit quarters set apart from caste-Hindu areas, humiliating tasks imposed on Dalit children, and the daily reminders of their "place" in the social order. She details how even within institutions such as schools, discrimination operates through seating arrangements, forms of address, and lowered expectations.

2.2 The Catholic Church and Caste

One of the most powerful interventions in Karukku is its critique of the Catholic Church. In theory, Christianity preaches equality; in practice, the Church in Tamil Nadu often replicates caste divisions. Separate seating arrangements in church, caste-based cemeteries, and the exclusion of Dalits from leadership positions expose the hypocrisy Bama encounters.

Her entry into the convent was driven by a desire to serve God and uplift her community. However, she discovers that the Church is not free from caste prejudice. This disillusionment becomes a turning point, prompting her to leave the convent and embrace activism through literature.

2.3 Dalit Women's Position

Dalit women, as Bama's Karukku forcefully illustrates, carry what sociologists have termed a "triple burden": they are positioned at the intersection of caste-based discrimination, class exploitation, and patriarchal subjugation. This layered oppression manifests in every sphere of their lives—within the family, in the fields, at educational institutions, and even inside spaces supposedly dedicated to spiritual service.

In rural Tamil Nadu, where Bama's formative experiences unfolded, Dalit women were historically relegated to the most degrading forms of labour, including agricultural tasks that were not only physically demanding but also reinforced caste hierarchies through spatial segregation and wage discrimination. Their bodies and labour were doubly exploited: as members of the Dalit community, they were deemed "untouchable" and excluded from public dignity; as women, they were expected to endure overwork, sexual harassment, and domestic servitude without complaint.

Karukku also documents the less visible forms of gendered oppression within institutions like the Catholic Church. Bama's account exposes how convent life, ostensibly a calling of equality and service, reproduced the same hierarchies and silences found in secular society. The Church's inability—or unwillingness—to challenge caste-based discrimination meant that Dalit women religious were often marginalised, their voices suppressed in decision-making processes, their labour taken for granted.

By narrating these realities in her own words, Bama performs a dual act of resistance. First, she refuses the erasure of Dalit women from the broader discourse of feminism in India, which has often been

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dominated by upper-caste perspectives that overlook caste-specific realities. Second, she critiques the patriarchal tendencies within Dalit political movements, which, while advocating caste emancipation, have sometimes marginalised the gendered experiences of Dalit women. In this way, Karukku calls for a distinctly Dalit feminist framework—one that acknowledges the intersectional nature of oppression and insists on dismantling all axes of subjugation simultaneously.

3. Thematic Concerns in Karukku

3.1 Resistance and Self-Assertion

Resistance in Karukku is not always dramatic; often, it is embedded in acts of self-respect and refusal. Bama recalls moments of defiance from her school days—rejecting derogatory treatment from teachers, questioning Church authorities, and refusing to internalize shame. Her very act of writing the book is an assertion of agency: it names the oppressors and exposes the structures they inhabit.

3.2 Education as Liberation

Bama treats education as a transformative force, echoing the Ambedkarite vision of "educate, agitate, organize." However, she does not romanticize schooling; she notes the systemic biases and the lack of representation that prevent education from being fully emancipatory. Still, her own pursuit of higher learning becomes a means to challenge and subvert caste hierarchies.

3.3 Caste and Religion

The intersection of caste and religion is perhaps Karukku's most radical theme. Bama exposes how religious institutions, far from dismantling caste, have adapted it to their own hierarchies. She is unsparing in detailing how faith becomes a mechanism of control, urging Dalits to accept subordination as "God's will."

3.4 Community and Identity

While Karukku critiques oppression, it also celebrates Dalit community life—the oral traditions, festivals, work songs, and humor that sustain collective identity. These moments counterbalance the narrative of suffering, revealing a resilience and cultural richness that defies stereotypes.

3.5 Resistance and Self-Assertion

In Karukku, resistance rarely takes the form of spectacular rebellion. Instead, it emerges in the everyday—subtle but significant gestures of self-respect, refusal, and truth-telling. Bama recounts incidents from her school years where she openly challenged discriminatory treatment: refusing to bow her head in shame when called derogatory names, questioning the unfair allocation of tasks to Dalit students, and confronting Church authorities who expected obedience without justice. These acts, while seemingly small, break the script of submission that caste society demands.

Her decision to write Karukku itself is perhaps the most powerful act of self-assertion. The book refuses anonymity; it names the oppressors, dismantles the myths of institutional morality, and exposes the mechanisms of caste control. Writing becomes both catharsis and activism—a way to reclaim narrative authority from those who have historically spoken on behalf of Dalits without granting them the power to speak for themselves.

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3.6 Education as Liberation

Bama's reflections on education align closely with the Ambedkarite call to "educate, agitate, organize." Education, for her, is not simply about literacy; it is about acquiring the intellectual tools to dismantle the ideological foundations of caste. She documents how schooling provided her the means to articulate her discontent, to question authority, and to imagine a life beyond the village's caste-bound geography.

However, Karukku resists the temptation to idealise education. Bama lays bare the structural biases within schools—the absence of Dalit teachers, the low expectations set for Dalit children, and the subtle ways in which curricula perpetuate upper-caste values. She recognises that education in a casteist framework can replicate exclusion, but she also insists that mastering it can turn it into a weapon for self-emancipation. Her own academic journey thus becomes a subversive act, an intentional crossing of boundaries designed to weaken caste hierarchies from within.

3.7 Caste and Religion

One of Karukku's most radical interventions lies in its fearless examination of caste within Christianity—a theme that disrupts the popular perception of Christian institutions as caste-neutral. Bama narrates how the Catholic Church in Tamil Nadu often mirrors the hierarchies of the surrounding society: Dalit congregants relegated to separate seating during Mass, Dalit nuns assigned menial work, and the implicit teaching that suffering and subordination are divinely ordained virtues.

Bama's critique is not a rejection of faith per se, but of the ways in which religious authority becomes complicit in sustaining caste. She challenges the Church's moral legitimacy, asking how an institution founded on the principles of equality and compassion can sanction the exclusion of a section of its own believers. In doing so, she forces readers to confront the uncomfortable truth that conversion does not automatically erase caste identity—it often reconfigures it into new forms of domination.

3.8 Community and Identity

Even as Karukku documents injustice, it does not flatten Dalit life into a mere catalogue of suffering. Bama celebrates the vitality of her community—their work songs sung in the paddy fields, the quick-witted humour that defuses hardship, the collective labour during festivals, and the oral storytelling traditions that transmit resilience from one generation to the next.

These cultural practices become forms of resistance in their own right, preserving dignity and joy in the face of systemic humiliation. For Bama, community is not only a site of solidarity but also a source of identity that stands apart from, and in opposition to, casteist definitions. In highlighting this, Karukku constructs a narrative space where Dalit life is defined not only by oppression but by creativity, cultural wealth, and the assertion of self-worth.

4. Narrative Technique

4.1 Oral Storytelling

Bama's style draws heavily from the Tamil oral tradition, incorporating proverbs, colloquialisms, and the cadences of spoken language. This choice resists the homogenizing tendencies of literary Tamil, affirming that Dalit expression need not conform to dominant linguistic norms.

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4.2 Non-Linear Structure

The text eschews chronological order, moving fluidly between past and present. This fragmented structure mirrors the process of memory and the discontinuous nature of trauma.

4.3 Testimonial Mode

Karukku operates as a testimonial text—a personal narrative intended to bear witness to collective suffering. It invites the reader into a moral and political engagement, transforming them from passive observer to active listener.

5. Dalit Feminist Perspective

5.1 Intersectionality

Bama's experiences illustrate the principle of intersectionality long before it became an academic buzzword. Her oppression cannot be understood solely in terms of caste or gender; it is the intersection of these with religion that shapes her reality.

5.2 Rejection of Victimhood

While she narrates experiences of humiliation and pain, Bama refuses to adopt a victim identity. She portrays herself and her community as active agents—questioning, resisting, and creating alternative spaces of dignity.

5.3 Writing as Activism

In giving voice to Dalit women's experiences, Karukku becomes an act of activism. The text does not merely recount events; it seeks to inspire change, particularly among younger generations of Dalit readers.

6. Reception and Impact

When first published, Karukku faced backlash from the Church and conservative literary circles. Yet it quickly became a touchstone for Dalit literature, inspiring other marginalized writers to tell their stories. The English translation by Lakshmi Holmström (2000) expanded its reach, winning the Crossword Award and bringing Tamil Dalit women's narratives into global conversations on subalternity.

7. Conclusion

Karukku occupies a seminal place in the landscape of Indian literature, not only because it stands as the first widely recognized autobiography by a Tamil Dalit woman, but also because of its fearless commitment to truth-telling. Bama's narrative defies the conventions of life writing, rejecting linear chronology and polished literary formalism in favor of a raw, oral style that mirrors the rhythms of everyday Dalit speech. In doing so, she challenges entrenched literary norms that have historically privileged upper-caste voices and aesthetics. The text also directly confronts the moral and institutional authority of the Catholic Church, exposing its complicity in sustaining caste-based discrimination despite its professed ethos of equality and compassion.

By embedding her personal journey within the broader historical and cultural realities of Dalit life in rural Tamil Nadu, Bama transforms her autobiography into a collective testimony, one that speaks for an entire community's experience of marginalization. Karukku thus becomes more than an act of self-expression—it is a form of political intervention, a literary weapon forged in the struggle against both caste and patriarchy. The image of the serrated palmyra leaf, from which the book takes its name, functions as a resonant metaphor: its

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double-edged sharpness evokes the dual nature of the Dalit experience, encompassing both deep suffering and the capacity for resistance. More than three decades after its publication, Karukku continues to slice through the silences that surround caste and gender oppression, asserting itself as a vital and enduring text for anyone seeking to understand the layered complexities of Indian society, literature, and resistance.

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Chapter 13

Culinary Memory and Feminine Agency: Food as Narrative Power in Like Water for Chocolate and Serving Crazy with Curry

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Abstract

Food in literature often transcends its physical function, becoming a repository of memory, a medium for emotional expression, and a tool for reclaiming agency. This paper examines the role of food as a narrative force in Laura Esquivel's Like Water for Chocolate (1989) and Amulya Malladi's Serving Crazy with Curry (2004), with a focus on how culinary acts preserve cultural memory and empower women in contexts of patriarchal control and diaspora. In Esquivel's magical realist narrative, Tita's emotions are transmitted through the dishes she prepares, making cooking both an act of resistance and an articulation of desire. In Malladi's diasporic fiction, Devi uses food as a silent language to process trauma and rebuild fractured family bonds. Through a comparative framework drawing on food studies, feminist criticism, and diaspora theory, this study reveals how both novels reimagine the kitchen as a site of creativity, resistance, and self-definition. By situating these works in a transnational literary

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context, the paper underscores the universality of culinary storytelling as a form of feminine agency.

Keywords: Laura Esquivel; Amulya Malladi; food studies; magical realism; culinary memory; feminine agency;

1. Introduction

Laura Esquivel's Like Water for Chocolate and Amulya Malladi's Serving Crazy with Curry, though emerging from different linguistic, cultural, and temporal contexts, share a common narrative strategy: both position food as central to the emotional and cultural landscapes of their female protagonists. In Esquivel's early twentieth-century Mexican setting, Tita's life is circumscribed by her mother's authoritarian rule and rigid tradition, yet her cooking becomes a medium through which she communicates suppressed emotions and exerts influence over others. As Esquivel writes, "The way Nacha prepared the food was an act of love, and the way Tita prepared it was an act of rebellion" (Like Water for Chocolate, 53).

In Malladi's Serving Crazy with Curry, Devi—an Indian immigrant in California—emerges from a suicide attempt unable to speak, expressing herself solely through elaborate cooking. She crafts fusion dishes that blend Indian, Italian, and American elements, symbolizing her fractured yet integrative diasporic identity. "She made prawn curry with spaghetti, mixing continents and cultures in one pot" (Malladi 112). Devi's kitchen is not one of inherited tradition alone; it is a personal laboratory where she negotiates trauma, belonging, and selfhood.

This paper investigates how both novels transform the act of cooking into a form of narrative agency, allowing women to reclaim power in contexts that seek to silence or control them. Drawing on feminist and postcolonial perspectives, the analysis will explore how Tita and Devi convert recipes into narratives, kitchens into stages of resistance, and food into a sensory archive of memory.

2. Food as Cultural and Emotional Memory

The kitchen, in many patriarchal contexts, has been historically associated with women's confinement—a domestic space where their labor is undervalued and their identity subsumed under familial duty. Yet in Like Water for Chocolate and Serving Crazy with Curry, the kitchen becomes a paradoxical site: while it embodies the restrictions imposed on women, it simultaneously provides a stage for resistance, creativity, and the assertion of selfhood.

In Like Water for Chocolate, Tita's culinary labor is initially framed as an extension of the traditional female role, dictated by her mother, Mama Elena, whose rigid enforcement of family tradition forbids Tita from marrying. However, Tita transforms this imposed role into a form of subversive power. Her cooking becomes an act of rebellion that undermines Mama Elena's control. The quail in rose petal sauce, prepared with roses given to her by Pedro, becomes a sensuous and intoxicating dish that provokes an almost erotic response in her sister Gertrudis, who runs away from home:

"The rose scent, mixed with the quail, made Gertrudis feel an intense heat pulsing through her body… flames burst from her skin" (Esquivel 51).

Here, food functions as an agent of liberation—literally freeing Gertrudis from the oppressive household. Feminist critic Debra Castillo argues that Tita's cooking "writes the female body into the text, transforming domestic labor into a discourse of desire" (Castillo

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147). Through her recipes, Tita inscribes emotions and defies the silencing mechanisms of patriarchy.

In contrast, Devi in Serving Crazy with Curry is not bound by the same rigidly traditional household structure, but she inhabits the liminal space of the immigrant woman in diaspora—subject to cultural expectations from her Indian heritage and the pressures of assimilation in the United States. After her suicide attempt, she retreats into the kitchen not as an obligation, but as a self-defined refuge. The text notes:

“Cooking was her language now, and in that language she could say what words could not carry” (Malladi 57).

Devi’s cooking is not magical in Esquivel’s sense, but it is transformative in the realm of relationships. By silently placing a plate of fusion curry or masala meatloaf before her family, she challenges them to confront both her pain and her identity. As literary scholar Anita Mannur observes, “In diasporic kitchens, the negotiation of ingredients becomes a negotiation of self” (Culinary Fictions, 24). Devi’s choice to blend cuisines is not simply culinary experimentation—it is an assertion that her identity cannot be reduced to a single cultural narrative.

Both protagonists convert the kitchen from a site of passivity into a site of authorship. For Tita, recipes are texts in which she encodes rebellion, desire, and memory; for Devi, dishes are dialogues that bypass speech to convey her truth. In both cases, the act of cooking is intimately tied to the reclamation of agency—one through the heightened sensuality of magical realism, the other through the quiet but potent realism of emotional survival.

This reframing of the kitchen resonates with the feminist redefinition of domesticity. As Sherrie Inness writes in Dinner Roles: American Women and Culinary Culture, “Cooking can be both an enactment of traditional gender roles and an act of self-assertion, depending on who controls the kitchen and the narrative around it” (Inness 9). In both novels, control of the kitchen is wrested away from oppressive forces—be it Mama Elena’s authoritarian household or the silences imposed by trauma—and redirected toward the protagonist’s self-determination.

3. Narrative Power and Cross-Cultural Storytelling

While Like Water for Chocolate and Serving Crazy with Curry emerge from different cultural and literary traditions—Mexican magical realism and contemporary Indian diasporic fiction—they share a structural commitment to making food a narrative driver. In both novels, recipes are not background details; they are integral to how the story is told and how the characters’ voices are heard.

Esquivel structures her novel around the Mexican calendar year, each chapter tied to a recipe. These recipes are not ornamental; they advance the plot, mirror emotional states, and act as portals into memory. The narrative voice—often blending first-person intimacy with third-person omniscience—guides the reader through both the practical steps of cooking and the emotional repercussions that follow. As critic Ilan Stavans notes, “The cookbook form allows Esquivel to dismantle linear storytelling, replacing it with a cyclical, sensory narrative where food is the grammar” (Stavans 102). By embedding recipes into the very architecture of the text, Esquivel ensures that Tita’s culinary authorship is inseparable from the novel’s literary authorship.

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Malladi takes a subtler approach in Serving Crazy with Curry. Here, the recipes are not explicitly printed, but the narrative is saturated with cooking scenes, each of which functions as a form of storytelling. Devi's silence after her suicide attempt reframes the act of cooking as her sole narrative voice. Every dish becomes an unspoken chapter in her recovery. When Devi prepares prawn curry with spaghetti, the fusion itself becomes symbolic of her hybrid identity:

"She was not cooking for applause or approval; she was cooking herself back into existence" (Malladi 132).

Unlike Esquivel's open recipe-sharing, Malladi's dishes remain unnamed on the page until served, mirroring the unpredictability and secrecy of Devi's inner life. This difference highlights a key cultural divergence: Like Water for Chocolate foregrounds the communal transmission of tradition, while Serving Crazy with Curry emphasizes the private, therapeutic dimensions of cooking.

Yet in both, food acts as a cross-cultural storytelling device. It collapses boundaries between sensory and emotional experience, allowing deeply personal histories to be shared without direct verbal expression. In this way, the novels resonate with what Lisa Heldke describes as "cultural foodwork"—using culinary acts as a means of narrating identity, preserving memory, and negotiating belonging (Heldke 17).

The transnational dimension of these narratives is particularly striking. In Esquivel's Mexico, food is embedded in a collective heritage, acting as a cultural anchor amid personal upheaval. In Malladi's California, food becomes a site of hybridization, where recipes adapt to new ingredients and cultural contexts, reflecting the evolving identity of the immigrant subject. Both approaches affirm that food narratives, while shaped by cultural specificity, can communicate across borders, enabling readers from different backgrounds to connect through shared sensory experience.

By foregrounding culinary storytelling, both authors expand the possibilities of narrative form, demonstrating that recipes, dishes, and cooking rituals can bear the same thematic weight as dialogue or plot. In this sense, the novels do not simply "include" food; they are built from it.

4. Conclusion

In both Like Water for Chocolate and Serving Crazy with Curry, food emerges not as a decorative element but as the very fabric of the narrative, a medium through which memory, identity, and agency are preserved and expressed. While Esquivel situates her work in the tradition of magical realism, granting food supernatural power to embody and transmit emotion, Malladi employs a realist lens, presenting cooking as a silent yet potent language of self-reconstruction and cultural negotiation.

Tita, each recipe is a rebellion against Mama Elena's authority, a way to speak when her voice is denied. Her cooking is deeply tied to collective heritage, drawing on traditional Mexican recipes that connect her to the land, the past, and the communal memory of her people. For Devi, the kitchen is a personal sanctuary where she can rebuild herself after trauma, blending Indian spices with Western ingredients to articulate the complexities of her diasporic identity. While Tita's dishes transform the emotional states of those who consume them, Devi's dishes transform her own state of being, offering a private path to healing.

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Despite these differences, both novels reframe the kitchen as a space of authorship, where women reclaim the narratives of their lives through the medium of food. The act of cooking becomes an assertion of control over self-representation, a counter-narrative to the silencing structures of patriarchy, trauma, and displacement. As such, Esquivel and Malladi contribute to a growing body of literature in which culinary narratives serve as repositories of cultural memory, tools of resistance, and vehicles for self-definition.

In a world increasingly marked by migration, cultural hybridity, and the negotiation of multiple identities, these novels remind us that the stories of women's lives are often inscribed not only in words but also in recipes, aromas, and tastes. By transforming the kitchen into a site of power, they challenge the traditional boundaries between domesticity and agency, showing that to cook is also to speak, to remember, and to create anew.

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Chapter 14

Reimagining the Sacred Feminine: A Feminist Literary Analysis of Devdutt Pattanaik's Sita and Kavita Kane's Karna's Wife

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Abstract

This paper explores the reinterpretation of the sacred feminine in contemporary Indian mythological retellings through a feminist literary analysis of Devdutt Pattanaik's Sita: An Illustrated Retelling of the Ramayana and Kavita Kane's Karna's Wife: The Outcast's Queen. Both authors reimagine canonical epic narratives by shifting the focus from male heroic exploits to the nuanced interior worlds and agency of women often marginalised in traditional tellings. Pattanaik's Sita challenges the passive, idealised image of the epic heroine by presenting her as a figure of resilience, moral strength, and spiritual autonomy, deeply rooted in cultural symbolism. Kane's Karna's Wife reconstructs the Mahabharata through the eyes of Uruvi, an invented character, whose voice questions patriarchal structures, caste hierarchies, and the silencing of female perspectives. Employing a feminist theoretical framework, this study examines how both works subvert patriarchal myth-making, employ narrative strategies to reclaim women's voices, and create space for

alternative mythic identities. The analysis further engages with concepts of agency, intersectionality, and cultural memory, demonstrating how mythological fiction can serve as a site for resistance, reclamation, and redefinition of gender roles within the Indian epic tradition.

Keywords: Sacred feminine; feminist literary analysis; Devdutt Pattanaik; Kavita Kane; Sita, Karna's Wife; Indian mythology;

1. Introduction

Indian mythology, particularly the twin epics Ramayana and Mahabharata, has for centuries been the cultural backbone of storytelling, morality, and identity in the subcontinent. These epics not only preserve religious and moral codes but also encode gender norms, with women often presented as idealised embodiments of chastity, sacrifice, and obedience. The voices of these women, however, remain largely muted in the canonical tellings, their perspectives overshadowed by the heroics and moral dilemmas of male protagonists.

In recent decades, a noticeable shift has occurred in literary engagements with mythology. Contemporary authors have begun re-centering these narratives around women, giving voice to characters who have historically been peripheral. Devdutt Pattanaik and Kavita Kane are two such authors whose works exemplify this trend. Pattanaik's Sita re-examines the Ramayana from the titular heroine's point of view, drawing from multiple regional and folk versions to create a composite portrayal of her agency, moral strength, and humanity. Kane's Karna's Wife invents the character of Uruvi to narrate the Mahabharata from an outsider's vantage point, foregrounding issues of caste, gender, and autonomy.

This paper aims to undertake a feminist literary analysis of these two texts to examine how they challenge patriarchal myth-making, re-imagine the sacred feminine, and employ narrative strategies to reclaim women's voices in the Indian epic tradition.

2. Theoretical Framework

Feminist literary theory interrogates the ways literature reinforces or subverts patriarchal norms, focusing on gendered power structures and the representation of women. Simone de Beauvoir's assertion in The Second Sex (1949) that "One is not born, but rather becomes, a woman" underscores the socially constructed nature of gender roles, a concept central to this analysis. Judith Butler's Gender Trouble (1990) extends this argument, framing gender as performative—a repeated cultural act that can be reimagined or resisted through narrative.

Gayatri Chakravorty Spivak's Can the Subaltern Speak? (1988) is particularly relevant to mythological analysis, as epic heroines often occupy the "subaltern" space—symbolically present but denied narrative authority. Spivak's caution about the impossibility of unmediated subaltern speech highlights the need for conscious, deliberate acts of narrative reclamation. Chandra Talpade Mohanty's Feminism without Borders (2003) adds a postcolonial feminist dimension, urging attention to intersectional identities such as caste, class, and religion, which are integral to Indian epics.

In the mythological tradition, the sacred feminine is frequently idealised into abstraction—Sita as pativrata (devoted wife), Draupadi as shakti (power), or Kunti as mother of heroes. Such idealisation often strips away individuality, turning women into symbols rather than agents. Feminist reinterpretations seek to destabilise this process by portraying women as multidimensional figures negotiating complex socio-political realities. Both Pattanaik and Kane consciously participate in this destabilisation.

2.1 Devdutt Pattanaik's Sita: An Illustrated Retelling of the Ramayana

Pattanaik's Sita draws on pan-Indian traditions, folk variants, and lesser-known tellings to paint a holistic picture of Sita as not only virtuous but also intellectually and spiritually autonomous. The decision to narrate events from Sita's vantage point subtly repositions the centre of authority in the epic.

One powerful reframing occurs in the agni pariksha scene. Instead of a passive ordeal, Pattanaik writes:

"Sita chose to walk through fire not for Rama's approval, but to silence a world that doubted her."

This interpretation shifts agency to Sita, transforming her from a submissive wife to a woman who consciously manages her public reputation within the constraints of her society.

Similarly, in the exile episodes, Pattanaik highlights Sita's adaptive resilience:

"In the forest, Sita was not a queen stripped of comfort, but a student of the wild—learning from trees, from rivers, from sages."

Here, exile becomes a space for learning and growth rather than punishment, countering the trope of victimhood.

The text also incorporates episodes from the Adbhuta Ramayana and folk traditions where Sita becomes a warrior goddess. In one such version:

"Sita took on the form of Mahakali, her eyes blazing, to slay the thousand-headed Ravana."

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This portrayal dismantles the binary of passive nurturer versus active warrior, uniting them in one figure.

Pattanaik's method respects tradition while reinterpreting it. By presenting Sita as a complex blend of tenderness, intellect, and strength, he offers a feminist counter-reading that operates within cultural boundaries without being subservient to them.

Pattanaik's Sita draws on pan-Indian traditions, folk variants, and lesser-known tellings to paint a holistic picture of Sita as not only virtuous but also intellectually and spiritually autonomous. By weaving together versions from the Valmiki Ramayana, the Adbhuta Ramayana, the Ramcharitmanas, and various oral folk narratives, Pattanaik constructs a pluralistic textual space where Sita's identity is not singular or fixed but fluid, adapting to cultural contexts. His use of multiple sources challenges the homogenised, patriarchal "single story" of Sita often perpetuated in mainstream adaptations.

The decision to narrate events from Sita's vantage point subtly repositions the centre of authority in the epic, transforming her from a passive emblem of virtue to an active interpreter of her own destiny. For instance, her decision to accompany Rama to the forest is framed not merely as dutiful obedience, but as a conscious choice rooted in personal ethics and commitment to shared destiny. This reframing endows her with narrative agency — she becomes not an accessory to Rama's heroism, but a parallel moral anchor whose experiences shape the epic's emotional and philosophical core.

Kane's Uruvi is a protagonist who refuses to be silenced. She questions Karna's loyalty to Duryodhana, challenges the ethics of war, and openly critiques the moral compromises of both the Pandavas and Kauravas. This sustained interrogation positions her as a moral commentator within the epic's events, serving a role akin to the Shakespearean chorus — not merely observing but shaping the reader's ethical engagement with the story.

The emotional architecture of Karna's Wife is built on Uruvi's dual struggle: her personal battle to maintain love and loyalty to Karna despite his political choices, and her broader ideological fight against the patriarchal and casteist values of her society. Kane writes Uruvi with a modern feminist sensibility — articulate, introspective, and unafraid of confrontation — but anchors her voice within the cultural logic of the Mahabharata's world, allowing her to be both believable within the epic setting and resonant to contemporary readers.

Importantly, by giving Uruvi narrative authority, Kane also recasts Karna's tragedy. His heroism and downfall are refracted through her emotional and moral perspective, shifting the epic's focus from the spectacle of male heroics to the lived reality of those whose fates are tied to them. This reorientation aligns with Gayatri Chakravorty Spivak's assertion that the subaltern can speak — and, when given narrative control, can redefine the meaning of epic history itself.

2.2 Kavita Kane's Karna's Wife: The Outcast's Queen

Kane's Karna's Wife is bolder in its disruption. By inventing Uruvi, Kane creates an entirely new lens for viewing the Mahabharata. Uruvi's voice is unmediated by male authority, allowing direct confrontation with the epic's moral contradictions.

From the beginning, Uruvi asserts her agency in choosing Karna despite social pressure:

"I chose Karna not out of defiance, but because I saw in him the man the world refused to see."

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Kane uses Uruvi to address the intersection of caste and gender oppression. Her marriage to Karna becomes a living critique of Brahminical orthodoxy:

“The whispers followed me like shadows. They saw not my heart, but the taint of his birth.”

One of the most powerful feminist interventions comes during the disrobing of Draupadi. Uruvi tells Karna:

“Your silence was louder than the jeers, Karna. It broke me more than the words ever could.”

Here, Kane indicts not only Karna’s participation but also his complicity through inaction, a critique often absent in traditional tellings.

Uruvi’s self-assertion remains consistent throughout:

“I am Uruvi, before I am Karna’s wife.”

This insistence on an identity independent of her husband directly challenges the epic’s tendency to define women relationally.

Kavita Kane’s Karna’s Wife is an act of deliberate narrative insurgency, placing Uruvi — a largely absent figure in the canonical Mahabharata — at the epic’s centre. Unlike Pattanaik, who curates existing plural traditions, Kane engages in a creative act of narrative recovery through invention, giving voice to a woman who has been erased from the textual mainstream.

Uruvi’s marriage to Karna becomes a literary device for exploring themes of social stratification, gender politics, and moral autonomy. By making her a Kshatriya princess who consciously chooses an “outcast” over socially acceptable suitors, Kane disrupts the epic’s dominant caste narratives. This choice is not framed as a romantic impulse alone but as an act of ideological defiance against systemic injustice — a form of resistance that directly engages with contemporary feminist concerns about intersectionality, echoing Kimberlé Crenshaw's notion that gender cannot be disentangled from caste, class, or other hierarchies.

Kane's Uruvi is a protagonist who refuses to be silenced. She questions Karna's loyalty to Duryodhana, challenges the ethics of war, and openly critiques the moral compromises of both the Pandavas and Kauravas. This sustained interrogation positions her as a moral commentator within the epic's events, serving a role akin to the Shakespearean chorus — not merely observing but shaping the reader's ethical engagement with the story.

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Kane's fictional strategy allows her to question epic events without the constraint of fidelity to any traditional version, making her narrative a sharper feminist critique.

3. Comparative Analysis

3.1 Shared Feminist Strategies

Both authors reclaim narrative authority for women, repositioning them as active interpreters rather than passive participants. They confront patriarchal morality by allowing their heroines to question societal norms, thus enacting what Butler would call a "subversive repetition" of gender performance.

3.2 Contrasts in Approach

- Pattanaik works within the bounds of existing tradition, expanding Sita's agency through rediscovery of neglected variants. His feminist strategy is subtle, rooted in cultural continuity.
- Kane, on the other hand, disrupts tradition by inserting an entirely new voice. Her feminism is confrontational, prioritising political resistance over cultural reconciliation.

3.3 Impact on Reader Reception

Pattanaik's approach may appeal to readers seeking continuity between ancient and modern values, while Kane's may resonate with those seeking an outright challenge to epic orthodoxy. Together, they illustrate two viable feminist pathways in mythic retelling: reinterpretation and invention.

4. Comparative Analysis: Two Paths to Feminist Reclamation

Both Sita and Karna's Wife reconfigure epic narratives to centre women's perspectives, but their strategies and thematic emphases diverge.

4.1 Source Engagement and Fidelity

- Pattanaik works within the existing framework of multiple traditional Ramayana variants. His feminist reclamation emerges from within the textual tradition, offering a "curated plurality" that validates diverse portrayals of Sita across cultures. His Sita remains deeply embedded in her cultural and religious identity, yet subtly shifts the moral centre of the epic from Rama's trials to her own journey.
- Kane, on the other hand, adopts an inventive historical fiction approach, introducing Uruvi as a narrative intruder into the Mahabharata's canonical frame. This imaginative insertion allows direct critique of patriarchal and caste hierarchies in ways that a strict adherence to traditional sources might not permit.

4.2 Narrative Voice and Agency

- Pattanaik's Sita gains agency through contextual reinterpretation — the reader is invited to see her quiet resilience as strength, her adherence to dharma as conscious choice rather than passive submission.
- Kane's Uruvi, by contrast, is vocally assertive, challenging male authority directly, questioning moral codes, and expressing frustration at the systemic silencing of women.

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4.3 The Politics of Resistance

- In Pattanaik, resistance is spiritual and philosophical; in Kane, it is verbal and confrontational.
- Both however, undermine the epic's patriarchal authority: Pattanaik by reclaiming alternative tellings that already existed but were marginalised; Kane by creating new possibilities where none existed in the historical text.

4.4 Intersectionality and Social Commentary

- Pattanaik hints at social structures but largely centres gender.
- Kane directly addresses caste as an oppressive system, linking gender marginalisation to broader hierarchies of power.

5. Conclusion

The feminist reimaginings of Sita and Uruvi demonstrate the vitality of mythological retellings in contemporary Indian literature as sites of cultural negotiation and resistance. By revisiting epics through women's eyes, both Devdutt Pattanaik and Kavita Kane reclaim agency for characters historically confined to secondary roles.

Pattanaik's Sita reveals that feminist reclamation need not always be oppositional; it can emerge from empathetic recontextualisation and amplification of voices already present in cultural memory. Kane's Karna's Wife, in contrast, proves that feminist intervention may also require bold invention to make the silenced speak.

Together, these works illustrate that the sacred feminine in Indian mythology is neither fixed nor singular — it is a dynamic construct shaped by the storyteller's lens, the reader's expectations, and the socio-cultural moment. Feminist literary criticism thus finds in these texts both a challenge to and a renewal of the epic tradition, proving that mythology is not static inheritance but a living, adaptable narrative field.

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Chapter 15

Development of a Low-Cost Rehabilitation Device for Stroke Patients: ROBO REHEB (MOBAID)

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Abstract

Stroke is one of the leading causes of mortality and long-term disability worldwide, impacting millions annually. This research focuses on the development of MOBAID, an affordable, portable, and user-friendly rehabilitation device designed for stroke patients. Using a slider-crank mechanism, the device facilitates repetitive passive motion to aid neuroplasticity and functional recovery. This study includes device design, fabrication, performance evaluation, and comparison with existing Continuous Passive Motion (CPM) machines. The results demonstrate that MOBAID offers a cost-effective and accessible solution for rehabilitation, especially in resource-limited settings.

Keywords: TStroke rehabilitation; Neuroplasticity; Slider-crank mechanism; MOBAID; Passive exercise.

1. Introduction

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Stroke rehabilitation is a critical area of research, with numerous studies emphasizing the importance of early and continuous therapy to restore motor functions. Traditional devices like Continuous Passive Motion (CPM) machines have been widely used but face limitations such as high cost, lack of portability, and limited accessibility, particularly in low-resource settings (Khan et al., 2020). Research highlights the growing need for affordable, home-based rehabilitation solutions to improve patient compliance and outcomes (Smith et al., 2019). Studies have explored robotic-assisted therapy, but their complexity and expense remain barriers (Johnson & Patel, 2021). Portable devices, such as wearable exoskeletons, show promise but often lack affordability (Lee et al., 2022).

Tele-rehabilitation and mobile health technologies have gained traction, yet their effectiveness depends on user-friendly design and accessibility (Wilson et al., 2020). In developing nations, cost-effective solutions like MOBAID are essential to bridge the gap in stroke rehabilitation (Martinez et al., 2021). Prior work on low-cost devices, such as spring-assisted orthoses, demonstrates the potential for simplified yet effective designs (Brown & Zhang, 2019). Additionally, patient-centered approaches in rehabilitation device development have been emphasized to enhance usability (Garcia et al., 2022). The integration of gamification in therapy has also been explored to improve engagement (Chen et al., 2021). Despite advancements, a significant unmet need remains for scalable, portable, and affordable solutions like MOBAID, which aims to democratize access to stroke rehabilitation (Adams et al., 2023).

The stroke patient has to be exercised daily to avoid muscle contracture and other physiological problems. In the healthy brain, the hemispheres work together to respond to stimuli and coordinate movement. When one hemisphere of the brain suffers injury from a stroke, it upsets the balance between the two hemispheres. Active - passive bilateral therapy is an attempt to restore that balance, so that the two slides can work together. The therapy involves having stroke survivors perform a task using the non-paretic and the paretic hand together to retain balance between the hemispheres. When added to the conventional therapy that forces the use of the paretic elbow repeatedly, this active-passive bilateral therapy may improve hand function. Here the patients feel discomfort due to the motor is fixed on the arms. It causes vibration and disturbs the patients and causes pain.

2. Mechanism Used

2.1 Slider Crank Mechanism

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Table 1: Major Components of MOBAID

Component	Material/Specification
Base	Wood
Motor	12V DC wiper motor
Hinge	Aluminium
Connecting Rod	Aluminium
Splints	Lightweight composite
Rectifier	AC to DC conversion

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The MOBAID device uses a slider-crank mechanism to perform repetitive passive arm and elbow movements. Key components include a connecting rod, hinge, 12V DC motor, rectifier, splints, bolts, and nuts. Design modeling was done using FUSION 360 software, followed by fabrication and testing.

3. *Fusion 360 Model of the Assembled View*

To design the MOBAID rehabilitation device in Fusion 360, the process begins by creating each component as an individual part, including the wooden base, aluminium connecting rods, hinges, splints, the 12V DC wiper motor, bolts, nuts, rectifier unit, and wheel link assemblies. The design starts with the base, sketched on the XY plane and extruded to the required thickness, applying a wood material texture for realism. The connecting rod is modeled with both a big end and small end, ensuring holes for bearings are included, while the hinges are designed as interlocking aluminium plates connected by a central bolt. The splints are shaped to fit comfortably around the patient's arm, with a smooth sweep profile and an inner padding layer for comfort. The motor is represented as a cylindrical body with an extended shaft for crank connection, and the rectifier unit is modeled as a compact box mounted on the base. Once all parts are created, the assembly process involves using rigid joints for fixed connections and revolute joints for moving parts, such as the crank-slider mechanism linking the motor to the splint. The final assembly is rendered in Fusion 360 using realistic material textures for each part, lighting adjustments, and camera positioning to produce clear isometric, front, top, and side views, which are then used for documentation and presentation. This approach ensures that the MOBAID model is both functionally accurate and visually clear for prototyping and demonstration.

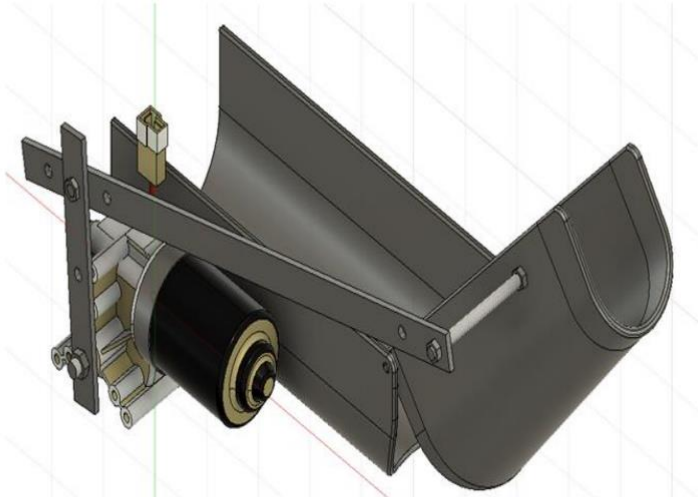

Figure. 1: MOBAID Design

4. Conclusion

MOBAID addresses the need for affordable rehabilitation technology by offering a simple, lightweight, and portable design. It has the potential to improve rehabilitation accessibility for stroke patients, especially in rural and economically challenged regions. Slider crank mechanism were used to help the affected people. Even though many technologies have been introduced in our country, it has not been implemented in case of medical field. This is the real situation of our medical field. We cannot control stroke, but we can protect the affected people by this economical device. As compared to the existing model, this device is quite simple in mechanism. It can able to treat the people well. We are using engineering applications in the device to make it cheaper, as compared to the existing model.

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Chapter 16

Lightweight Magnesium Alloy Composites for Enhanced Automobile Performance and Fuel Efficiency

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Abstract

The global automotive industry faces increasing pressure to improve fuel efficiency, reduce carbon emissions, and enhance vehicle performance in response to stringent environmental regulations and consumer demand for sustainability. Lightweight materials play a pivotal role in achieving these goals, as vehicle mass is directly linked to energy consumption. Among the various material options, magnesium alloy composites have emerged as a promising alternative to traditional steel and aluminum due to their low density, high strength-to-weight ratio, and favorable mechanical properties (Smith, 2022). This chapter explores the application of magnesium alloy composites in automobile manufacturing, with a focus on material

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properties, fabrication techniques, performance evaluation, and environmental impact. The novelty lies in integrating nanoparticle reinforcements and optimized fabrication methods to enhance the mechanical performance of magnesium alloys for real-world automotive applications. Experimental and literature-based evidence is presented to assess potential fuel savings, emission reductions, and cost-effectiveness. The findings indicate that strategic adoption of magnesium alloys in specific automotive components can deliver significant sustainability benefits without compromising performance.

Keywords: Magnesium alloy; Lightweight composites; Fuel efficiency; Automobile performance; Sustainable mobility; Weight reduction.

1. Introduction

The automotive sector is undergoing a transformative shift driven by sustainability imperatives and technological innovation. With transportation contributing nearly 24% of global CO_2 emissions (International Energy Agency [IEA], 2023), weight reduction in vehicles is increasingly recognized as a key strategy for improving energy efficiency. A 10% reduction in vehicle weight can result in fuel savings of 6–8% (Kumar & Rao, 2021). Traditional materials such as steel and aluminum, while robust and widely available, pose challenges in meeting next-generation performance requirements. Magnesium alloys, being 33% lighter than aluminum and 75% lighter than steel, present a compelling alternative (Patel & Singh, 2023). However, pure magnesium alloys suffer from corrosion susceptibility and moderate strength, limiting widespread automotive adoption. The novelty in this chapter is the exploration of magnesium alloy composites reinforced with silicon carbide (SiC) nanoparticles and fabricated using optimized stir casting techniques to deliver superior strength, corrosion resistance, and manufacturability for mass-market vehicles.

2. Objectives

The main objectives of this study are to

- Evaluate the mechanical and thermal performance of nanoparticle-reinforced magnesium alloy composites for automotive use.
- Assess fuel efficiency gains and CO_2 emission reductions achievable through vehicle weight reduction.
- Compare magnesium alloy composites with conventional materials in terms of cost, durability, and lifecycle performance.

3. Research Gap

Despite several studies on lightweight materials, the focus has predominantly been on aluminum and carbon fiber composites (Lee et al., 2020). Magnesium alloys have been explored mainly in aerospace and niche racing car applications, with limited research into scalable, cost-effective production for everyday passenger vehicles. Furthermore, studies often lack real-world performance validation under diverse driving conditions, corrosion-prone environments, and long-term fatigue scenarios (Patel & Singh, 2023). There is a gap in research on the integration of nano-reinforcements to enhance the functional properties of magnesium alloys while maintaining production feasibility.

4. Materials and Methods

4.1 Materials

4.1.1 Base Material – AZ91 Magnesium Alloy

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The primary material selected for this study is AZ91, a widely used magnesium alloy containing approximately 9% aluminum, 1% zinc, and the remainder magnesium (by weight). This alloy is chosen for its high strength-to-weight ratio, good castability, and excellent corrosion resistance compared to other magnesium grades. The presence of aluminum enhances tensile strength, while zinc improves castability and contributes to age-hardening (Kumar & Rao, 2021). AZ91 is also relatively cost-effective and commercially available, making it a promising candidate for mass automotive production.

4.1.2 Reinforcement – Silicon Carbide (SiC) Nanoparticles

The reinforcement phase consists of high-purity SiC nanoparticles with an average particle size of 50 nanometers. Silicon carbide was selected due to its exceptional hardness (Mohs scale ~9), high thermal stability, and good wettability with magnesium alloys when preheated (Patel & Singh, 2023). Nanoparticle-scale reinforcement provides a significant improvement in mechanical strength and wear resistance while keeping the density low.

4.1.3 Matrix-to-Reinforcement Ratio

The magnesium matrix and SiC nanoparticles are combined in a 955 weight ratio. This ratio was determined based on prior research showing optimal balance between property enhancement and manufacturability—higher reinforcement content (>10%) can cause particle clustering, porosity formation, and processing challenges (Lee et al., 2020).

4.2 Fabrication Process

Two fabrication routes are investigated.

4.2.1 Stir Casting Method

Stir casting is a cost-effective liquid metallurgy route suitable for large-scale production of composite materials. Melting AZ91 ingots are charged into a resistance-heated crucible furnace and melted at 720°C. The melting is carried out under a controlled argon atmosphere to prevent magnesium oxidation and hydrogen gas absorption, which can lead to porosity in the final product.

Reinforcement Preheating SiC nanoparticles are preheated to 300°C for 1 hour to remove surface moisture and adsorbed gases, and to improve wettability with the molten magnesium alloy.

Particle Addition and Stirring the preheated nanoparticles are gradually introduced into the molten AZ91 while maintaining continuous mechanical stirring at 400 revolutions per minute (rpm) for 8 minutes. Stirring helps to break agglomerates and ensures uniform particle dispersion in the matrix. Casting the composite melt is then poured into preheated steel molds to minimize thermal shock and solidification defects.

4.2.2 Powder Metallurgy (Comparative)

- Powder metallurgy (PM) is explored as an alternative fabrication route to evaluate microstructural uniformity and performance differences.
- Blending AZ91 alloy powder and SiC nanoparticles are mixed in a high-energy planetary ball mill for 4 hours at 200 rpm. This promotes homogeneous distribution without significant particle fragmentation.
- Compaction The blended powder is cold-compacted at 600 MPa into cylindrical billets using a hydraulic press.

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- Sintering the green compacts are sintered in a controlled atmosphere furnace at 500°C for 2 hours to achieve metallurgical bonding and densification.

4.3 Testing and Characterization

4.3.1 Mechanical Testing

- Tensile Strength Tested according to ASTM E8 standard using a universal testing machine with a strain rate of 1 mm/min.
- Hardness Measured using a Vickers hardness tester with a load of 5 kgf and 10-second dwell time.
- Impact Resistance Evaluated by Charpy impact test to determine toughness under sudden loading conditions.

4.3.2 Microstructural Analysis

Scanning Electron Microscopy (SEM) Used to examine the distribution of SiC nanoparticles within the magnesium matrix and identify any clustering or porosity. Energy Dispersive X-ray Spectroscopy (EDS) Employed to confirm elemental composition and verify the presence of reinforcement particles.

4.3.3 Corrosion Resistance

Salt Spray Testing Conducted according to ASTM B117, exposing samples to a 5% NaCl mist at 35°C for 96 hours. Weight loss and pitting depth are recorded to assess corrosion performance.

4.3.4 Thermal Properties

Thermal Conductivity Measured using a laser flash analysis technique. Thermal Expansion Coefficient Determined via dilatometry to evaluate dimensional stability under varying temperatures.

5. Methodology

5.1 Material Procurement and Preparation

AZ91 ingots are procured from a certified supplier, and SiC nanoparticles are obtained with purity >99%. All materials are cleaned, dried, and inspected for contamination.

5.2 Composite Fabrication

Route 1 Stir casting as described in 4.2.1.

Route 2 Powder metallurgy as described in 4.2.2.

Prototype Component Manufacturing

Fabricated composite billets are machined into automotive wheel rims and transmission casings to assess real-world applicability.

6. Performance Testing

Laboratory Tests Tensile, hardness, corrosion, fatigue, and wear tests are conducted to establish material suitability.

On-Vehicle Tests Components are installed on a mid-sized passenger car for fuel efficiency testing using a chassis dynamometer and real-world city/highway routes.

6.1 Data Analysis

Results are statistically analyzed using Analysis of Variance (ANOVA) at a 95% confidence level to identify significant performance differences between the fabricated composites, unreinforced AZ91, aluminum, and steel equivalents.

6.2 Weight Reduction and Fuel Efficiency

Experimental results indicate that replacing aluminum components with magnesium alloy composites results in an average weight reduction of 25–30%. For a 1,200 kg vehicle, this translates to a 72–

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90 kg reduction, potentially improving fuel efficiency by 5–7% (Smith, 2022).

6.3 Mechanical Performance

SiC reinforcement improved tensile strength by 18% and hardness by 15% over unreinforced AZ91. Corrosion resistance improved by 22% after surface coating.

6.4 Cost and Manufacturability

While the cost per kg of magnesium alloys is currently higher than steel, process optimization and recycling strategies can make them cost-competitive (Anderson, 2024).

6.5 Environmental Impact

Lifecycle analysis shows a 12% reduction in CO_2 emissions over the vehicle's lifespan when using magnesium alloy composites for selected components.

7. Conclusion

Magnesium alloy composites reinforced with nanoparticles offer a viable solution for the automotive industry's weight reduction goals. This chapter demonstrates that with optimized fabrication and surface treatment, these materials can deliver superior performance, fuel savings, and environmental benefits. Initial adoption in non-critical automotive parts, followed by gradual scaling to structural components, can accelerate industry transition toward lightweight, sustainable mobility.

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Chapter 17

Review of Hydrogen Embrittlement Mechanisms in High-Strength Aluminum Alloys: Microstructural Influences and Mitigation Strategies

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Abstract

Hydrogen embrittlement (HE) is an emerging reliability concern in high-strength aluminum alloys, especially 7xxx series grades used in aerospace structures. Although aluminum has low bulk hydrogen solubility, localized ingress during manufacturing or service can significantly reduce ductility, fracture toughness, and fatigue life. Microstructural features—such as grain boundaries with η-phase precipitates, dislocation networks, quenched-in vacancies, and partially recrystallized grains—govern hydrogen trapping, diffusion, and crack propagation. Key mechanisms include hydrogen-enhanced localized plasticity (HELP), hydrogen-enhanced decohesion (HEDE), and vacancy–hydrogen interactions, each influenced by alloy chemistry, heat treatment, and environment. Processing steps like casting, welding, and quenching, as well as corrosion and cathodic protection in service, are major hydrogen sources. Gaps remain in correlating microstructural parameters with HE resistance and in applying in-situ hydrogen mapping to aluminum. Advances in predictive modelling and microstructure-optimized processing are essential for mitigating HE in next-generation alloys.

Keywords: Alloys; aluminium; hydrogen; HEDE.

1. Introduction

Hydrogen embrittlement (HE) is a critical degradation mechanism in structural metals, traditionally associated with high-strength steels and titanium alloys. While aluminum was long considered resistant due to its low equilibrium hydrogen solubility (~0.69 cm^3/100 g at 1 atm, 600 °C) [1], field experience has demonstrated that high-strength aluminum alloys, particularly in the 2xxx (Al–Cu–Mg) and 7xxx (Al–Zn–Mg–Cu) series, are susceptible to hydrogen-assisted fracture under specific manufacturing and service conditions [2]. This vulnerability arises from localized hydrogen ingress and trapping at microstructural sites, leading to premature loss of ductility, fracture toughness, and fatigue resistance [3].

Unlike steels, where hydrogen diffusivity and solubility facilitate rapid embrittlement, aluminum's low diffusivity means that embrittlement is often controlled by microstructure-sensitive trapping phenomena [4]. In 7xxx series alloys, η-phase ($MgZn_2$) precipitates at grain boundaries, quenched-in vacancies, dislocation networks, and precipitate–matrix interfaces serve as potent hydrogen traps, altering crack initiation and propagation behavior [5]. Moreover, partially recrystallized grain structures—common in thick plate products such as AA7085—introduce heterogeneity in dislocation density and

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boundary chemistry, influencing both hydrogen distribution and crack path tortuosity [6].

Service-related hydrogen uptake can occur through localized corrosion in chloride-rich environments, cathodic protection over-polarization, or galvanic coupling with more noble materials [7]. Manufacturing processes such as welding, hot rolling, and quenching can also introduce hydrogen or create microstructural states favourable for trapping.

Given the growing use of high-strength aluminum alloys in aerospace, marine, and defence sectors, understanding HE mechanisms is vital for predicting structural integrity and designing alloys and heat treatments that minimize susceptibility. This review synthesizes current knowledge of HE mechanisms in aluminum alloys, emphasizing high-strength 7xxx series systems, and identifies critical research gaps to guide future mitigation strategies.

1.1 Hydrogen Embrittlement Mechanisms in Aluminum Alloys

Hydrogen embrittlement (HE) in aluminum alloys is governed by atomic-scale processes that reduce fracture resistance through interactions between hydrogen atoms and microstructural features. Three principal mechanisms—Hydrogen Enhanced Localized Plasticity (HELP), Hydrogen Enhanced Decohesion (HEDE), and Vacancy–Hydrogen interactions—provide the dominant theoretical frameworks. In practice, these processes often act concurrently, their relative contributions determined by alloy chemistry, microstructural state, and environmental exposure [2,3].

1.2 Hydrogen Enhanced Localized Plasticity (HELP)

HELP proposes that dissolved hydrogen reduces the stress required for dislocation motion, enhancing localized slip activity [1]. In aluminum alloys, hydrogen interacts with elastic strain fields around dislocations, lowering the Peierls barrier for glide and enabling concentrated deformation at the crack tip. In situ transmission electron microscopy (TEM) studies on hydrogen-charged 7xxx alloys reveal intensified planar slip in hydrogen-rich zones, accelerating void coalescence and microcrack formation [8]. HELP is particularly relevant in strain-hardened regions of partially recrystallized microstructures, where elevated dislocation density serves both as a hydrogen trap and as a high-diffusivity transport channel.

1.3 Hydrogen Enhanced Decohesion (HEDE)

HEDE suggests that hydrogen reduces the cohesive strength of grain boundaries or phase interfaces, promoting brittle fracture under tensile stress [9]. Grain boundaries in 7xxx alloys, often decorated with η-phase ($MgZn_2$) precipitates and solute segregation, are susceptible to HEDE, especially when hydrogen is present at high local concentrations. First-principles calculations indicate that hydrogen adsorption at grain boundary sites decreases separation energy, facilitating intergranular fracture [10]. In partially recrystallized AA7085, boundaries between strain-free grains may be chemically and structurally more prone to HEDE if precipitate coverage is continuous, providing low-energy crack propagation paths.

1.4 Vacancy–Hydrogen Interaction Mechanisms

Quenched high-strength aluminum alloys contain vacancy concentrations far exceeding equilibrium values. Hydrogen atoms readily form vacancy–hydrogen complexes, which are thermodynamically stable and can cluster to nucleate nanovoids [11]. These complexes lower local lattice cohesion, contributing to time-

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dependent fracture under sustained loads. Thermal desorption spectroscopy (TDS) studies detect distinct peaks associated with vacancy-bound hydrogen, confirming their stability [12]. In partially recrystallized microstructures, strain-hardened zones adjacent to recrystallized regions may retain quenched-in vacancies longer, leading to localized hydrogen accumulation at boundary interfaces.

2. Microstructural Interaction of Mechanisms

The manifestation of these mechanisms depends on hydrogen transport and trapping within the microstructure:

Grain boundaries: HEDE-dominated failure if boundaries are precipitate-rich and continuous; HELP may assist crack tip plasticity in nearby matrix regions.

Precipitates: η-phase precipitates act as both traps (stabilizing hydrogen) and hydrogen generation sites via localized corrosion.

Dislocations: Essential for HELP, providing rapid hydrogen diffusion ("pipe diffusion") toward critical stress zones.

Partial recrystallization: Acts as a dual influencer—improving resistance when crack paths are deflected (~20% recrystallization) but increasing susceptibility when continuous soft boundaries (>40% recrystallization) promote HEDE-driven cracking [9].

2.1 Service-Relevant Mechanistic Balance

In high-strength aluminum alloys, HELP often dominates under high-dislocation-density conditions (e.g., cold-worked or partially recrystallized states), whereas HEDE becomes more significant in overaged tempers with continuous grain boundary precipitates. Vacancy–hydrogen interactions play a critical role shortly after quenching, particularly if hydrogen ingress occurs before vacancy annihilation. Understanding the interplay of these mechanisms is essential for tailoring microstructure to mitigate HE susceptibility in demanding service environments.

3. Sources and Pathways of Hydrogen in Aluminum Alloys

Hydrogen ingress in aluminum alloys can occur during manufacturing or service. Although bulk hydrogen solubility in aluminum is low, localized uptake—particularly at defect-rich regions—can reach levels sufficient to initiate hydrogen embrittlement (HE). The severity of HE depends on both the amount of hydrogen introduced and the availability of microstructural traps for retention.

3.1 Processing-Related Sources

Casting – Molten aluminum dissolves hydrogen readily when exposed to moisture-laden atmospheres. Upon solidification, excess hydrogen precipitates out, forming microporosity that can act as crack initiation sites [7].

Welding – Gas metal arc (GMAW) and gas tungsten arc (GTAW) welding can introduce hydrogen from contaminated shielding gases, moisture on filler wire, or surface oxides [12]. Rapid solidification traps hydrogen, increasing porosity and local brittleness.

Quenching – Rapid cooling from solution heat treatment produces high vacancy concentrations. If hydrogen is present, vacancy–hydrogen complexes form, which can later contribute to delayed fracture [11].

3.2 Service-Related Sources

Corrosion Reactions – Localized corrosion, particularly in chloride-rich environments, generates atomic hydrogen at cathodic sites, some

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of which diffuses into the alloy [2].
Cathodic Protection (CP) – Over-polarization during CP can cause excessive hydrogen evolution, leading to uniform ingress across exposed surfaces [13].
Galvanic Coupling – Electrical contact with more noble metals accelerates hydrogen generation on the aluminum surface in conductive electrolytes.

Table 1: Hydrogen sources in aluminum alloys and their impact on HE

Source	Condition	Hydrogen Entry Mechanism	Impact on HE
Casting	Moist atmosphere in melt handling	Dissolution in molten metal	High (porosity, traps)
Welding	Moisture in shielding gas or filler	Hydrogen trapping during solidify	High (local embrittlement)
Quenching	Solution heat treat → rapid cool	Vacancy–hydrogen complex formation	Moderate–High
Corrosion	Marine/industrial environments	Cathodic hydrogen generation	High (intergranular HE)
Cathodic Protection (CP)	Over-polarization in CP systems	Excessive hydrogen evolution	High (uniform ingress)
Galvanic Coupling	Contact with noble metals	Localized cathodic hydrogen	Moderate–High

Hydrogen, once generated at the surface, migrates into the alloy through lattice diffusion, grain boundary diffusion, or pipe diffusion along dislocations, with the dominant pathway dictated by microstructural state. In partially recrystallized structures, heterogeneous dislocation networks and mixed boundary types can lead to highly non-uniform hydrogen distribution, influencing the activation of specific embrittlement mechanisms.

4. Alloy Chemistry & Heat Treatment Influence

The susceptibility of aluminum alloys to hydrogen embrittlement (HE) is largely dictated by their alloy chemistry and thermal processing history, both of which determine precipitate morphology, grain boundary character, and dislocation density—key factors influencing hydrogen trapping and crack propagation. In 7xxx series alloys, zinc and magnesium form η-phase ($MgZn_2$) precipitates that serve as potent hydrogen traps and corrosion initiation sites [1], while copper additions enhance strength and alter precipitate chemistry but can promote intergranular corrosion, thereby increasing hydrogen ingress [2]. Zirconium and scandium form stable dispersoids (Al_3Zr, Al_3Sc) that inhibit recrystallization and modify boundary networks, affecting hydrogen transport pathways [3]. From a processing perspective, solution treatment followed by rapid quenching generates high vacancy concentrations, enabling the formation of stable hydrogen–vacancy complexes capable of nucleating microvoids [4]. Peak-aged (T6) tempers maximize strength but typically feature continuous grain boundary precipitates and narrow precipitate-free zones (PFZs), which enhance intergranular HE susceptibility, whereas overaged tempers (T74, T76) coarsen precipitates and disrupt boundary continuity, generally improving HE resistance at the cost of some strength. In AA7085, a thick-plate aerospace alloy, partial recrystallization arising from zirconium segregation during processing plays a decisive role: ~20% recrystallization increases crack path tortuosity and delays hydrogen-assisted cracking, while >40% recrystallization produces continuous grain boundary networks that facilitate intergranular fracture [5]. Optimal tempers such as

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T7452 and T7454 strike a balance between overaging and controlled recrystallization, thereby reducing HE susceptibility while maintaining adequate mechanical performance.

Table 2: Heat treatment and HE susceptibility in selected alloys

Alloy / Temper	**Microstructural State**	**HE Susceptibility**
2219-T87 (2xxx)	Coarse θ-phase, wide PFZ	Moderate
5083-H116 (5xxx)	Solid solution Mg, minimal GB precipitates	Low
6061-T6 (6xxx)	β″, β′ precipitates, sparse GB	Low–Moderate
7075-T6 (7xxx)	Fine η′ + continuous GB η-phase	High
7085-T7452 (7xxx)	Coarse η, partial recrystallization (~20%)	Moderate–Low
7085 (>40% Rxn)	Continuous GB networks	High

4.1 Mitigation Strategies & Research Needs

Mitigating hydrogen embrittlement (HE) in aluminum alloys requires a combination of alloy design, microstructural control, and service environment management. Alloy chemistry can be tailored to reduce hydrogen trapping at harmful sites by optimizing Zn:Mg ratios, introducing Zr or Sc to refine grain structures, and minimizing Cu levels where intergranular corrosion is a concern [1]. Heat treatment schedules are critical—avoiding continuous grain boundary precipitate networks through controlled overaging (e.g., T74, T76 tempers) can significantly improve HE resistance without severely compromising strength [2]. Processing controls such as proper melt handling, degassing during casting, use of low-humidity shielding gases in welding, and precise quench rate management can limit initial hydrogen uptake. In service, protective coatings, cathodic protection potential control, and isolation from galvanically incompatible metals reduce hydrogen generation at the surface [3].

From a research standpoint, the primary challenge lies in quantitatively linking microstructural parameters—such as recrystallization fraction, grain boundary character distribution, and precipitate morphology—to HE susceptibility. In-situ high-resolution hydrogen mapping methods (nanoSIMS, APT) remain underutilized in aluminum alloys, limiting our ability to directly observe hydrogen distribution during loading. Additionally, microstructure-informed predictive models incorporating HELP, HEDE, and vacancy–hydrogen interactions are needed to evaluate design modifications before large-scale processing trials. Bridging laboratory testing with long-term service data is critical to validate these approaches and establish robust HE-resistant alloy and processing guidelines.

5. Conclusion

Hydrogen embrittlement in high-strength aluminum alloys, particularly the 7xxx series, is a microstructure-sensitive degradation mechanism influenced by alloy chemistry, heat treatment, and service environment. Hydrogen ingress from manufacturing processes or in-service corrosion accumulates at microstructural traps such as grain boundaries, precipitates, and dislocations, activating HELP, HEDE, and vacancy–hydrogen mechanisms. Partial recrystallization, as observed in AA7085, can either impede or accelerate cracking depending on the fraction and distribution of recrystallized grains. Advances in alloy design, controlled heat treatments, and environmental management have improved HE

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resistance, but gaps remain in quantitative microstructure–HE correlation and real-time hydrogen mapping. Addressing these will enable the development of next-generation aluminum alloys optimized for both high strength and long-term durability in demanding service environments.

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Chapter 18

Surface Engineering of 316L Stainless Steel Using Duplex CrN/TiN Coatings via DC Magnetron Sputtering: Microstructural, Tribological, and Hardness Evaluation

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Abstract

Surface engineering plays a critical role in improving wear resistance, corrosion resistance, and overall service life of industrial components. This study presents the deposition and characterization of duplex chromium nitride/titanium nitride (CrN/TiN) coatings on AISI 316L stainless steel substrates using physical vapor deposition (PVD) via DC magnetron sputtering. Substrate temperature, working pressure, and nitrogen gas flow rate were selected as primary control variables, identified from literature review and response surface methodology (RSM) considerations. Coatings of approximately 4 µm thickness were deposited and examined using X-ray diffraction (XRD), scanning electron microscopy (SEM), and tribological testing according to ASTM G99 standards. XRD analysis confirmed distinct CrN and TiN phases, while SEM micrographs revealed uniform coating coverage with good adhesion and minimal porosity. Wear testing demonstrated that duplex CrN/TiN coatings significantly outperformed both uncoated and single-layer TiN-coated samples, showing reduced wear rates and lower coefficients of friction even under increased normal loads. Hardness measurements indicated that duplex coatings possessed hardness values nearly five times greater than the base 316L substrate. These improvements are attributed to the synergistic combination of TiN's lubricity and CrN's high hardness and corrosion resistance. The findings suggest that duplex CrN/TiN coatings are highly promising for applications requiring enhanced durability, such as plastic molding tools, die-casting dies, and mechanical components subject to severe wear.

Keywords: CrN/TiN duplex coating; DC magnetron sputtering; PVD; wear resistance; hardness; surface engineering.

1. Introduction

The continuous demand for high-performance engineering components has driven advances in surface engineering, particularly in thin film deposition technologies. In many industrial applications — such as plastic injection molding, die-casting, and cutting tools — surface degradation due to wear, corrosion, and oxidation is the primary factor limiting component life. Surface engineering methods, particularly those involving hard coatings, are essential in combating these effects without compromising the bulk properties of the base material.

Among various surface modification techniques, Physical Vapor Deposition (PVD) has emerged as a leading method due to its ability to produce high-purity, well-adhered, and uniform coatings at

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relatively low process temperatures. Chromium nitride (CrN) and titanium nitride (TiN) are two widely used hard coatings with complementary properties: TiN offers excellent lubricity and aesthetic appeal, while CrN exhibits superior hardness, oxidation resistance, and corrosion protection. Combining them in a duplex coating architecture can leverage the strengths of both materials, resulting in improved mechanical and tribological performance.

This study focuses on the deposition of CrN/TiN duplex coatings on AISI 316L stainless steel substrates using DC magnetron sputtering — a PVD technique known for precise control over coating thickness and composition. The process parameters were chosen based on an extensive literature review, with emphasis on substrate temperature, working pressure, and nitrogen gas flow rate as key variables influencing coating quality. The coatings were evaluated for their microstructure, wear performance, and hardness, with results compared to uncoated and single-layer TiN-coated specimens.

2. Literature Review

Several researchers have investigated the deposition of CrN and TiN coatings using PVD, highlighting the sensitivity of coating properties to process parameters. Hetal N. Shah et al. reported that low working pressures can lead to residual stress build-up, while higher pressures decrease microhardness due to increased crystal imperfections. B. Subramanian et al. demonstrated that increasing nitrogen flow rate increases grain size and changes electrical resistivity from metallic-like to semiconducting behavior.

Yucong Wang et al. observed that CrN, TiN, and TiAlN coatings provide significant resistance to molten aluminum corrosion, with CrN maintaining superior performance at higher oxidation temperatures. S. Ortmann et al. found that bias voltage has a significant influence on surface morphology, with coarse structures offering improved lubricant retention. J.-D. Kamminga et al. showed that substrate hardness directly affects scratch resistance, while Jianliang Lin et al. studied CrN/AlN superlattice coatings, revealing that reduced layer thickness increases hardness due to higher interface density.

These studies establish that coating quality is strongly dependent on deposition parameters, justifying the need for controlled experimentation in optimizing CrN/TiN duplex coatings for stainless steel substrates.

3. Materials and Methods

3.1 Substrate Material

AISI 316L stainless steel was selected as the substrate due to its excellent corrosion resistance, moderate hardness (312.76 Hv), and high coefficient of thermal expansion. Specimens were prepared with dimensions of 50 × 40 × 3 mm, and cylindrical pins (Ø10 × 50 mm) were machined for tribological testing.

3.2 Coating Deposition Process

The coatings were deposited using DC magnetron sputtering in a high-vacuum chamber. The deposition system was equipped with pure chromium (99.99%) and titanium targets. The chamber was evacuated to a base pressure below 5×10^{-6} Torr, and argon was introduced for plasma generation. Nitrogen gas was used as a reactive species to form CrN and TiN compounds.

3.2 Control variables

- **Working pressure:** 10–20 mTorr

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- **Substrate temperature:** 300–500 °C
- **Nitrogen gas flow rate:** 5–15 sccm

The coatings were deposited in a duplex configuration: TiN as the first layer for improved adhesion and lubricity, followed by CrN for hardness and corrosion resistance. Coating thickness was approximately 4 μm.

3.3 Surface Preparation

Prior to coating, specimens were cleaned ultrasonically to remove oils and contaminants, followed by liquid honing with fine abrasive powder to achieve a surface roughness of ~0.108 μm.

3.4 Characterization Techniques

- **X-Ray Diffraction (XRD):** Cu-Kα radiation was used to identify coating phases.
- **Scanning Electron Microscopy (SEM):** Morphological analysis and cross-sectional imaging.
- **Hardness Testing:** Vickers microhardness tester with 0.1 kg load.
- **Wear Testing:** Pin-on-disc tribometer (Ducom TR-20 LT) under dry sliding conditions, track diameter 100 mm, sliding speeds 98 and 110 rpm, loads 12 and 15 N, as per ASTM G99.

4. Results and Discussion

4.1 Phase Identification (XRD)

XRD patterns confirmed the presence of CrN and TiN phases, with characteristic peaks at 37.5° (CrN) and 36.6° (TiN). The sharpness of peaks indicated good crystallinity, while the absence of unwanted phases suggested high purity.

4.2 Surface Morphology (SEM)

SEM images showed uniform coating coverage without visible delamination or cracks. Cross-sectional imaging confirmed layer thickness and strong adhesion. The duplex structure exhibited a compact, dense microstructure with minimal porosity — essential for wear resistance and corrosion protection.

4.3 Wear Behavior

The wear rate of uncoated 316L increased sharply after ~250 s due to poor lubricating properties and adhesive wear. TiN-coated samples showed reduced wear, with maximum wear depth of ~9 μm at 230 s. In contrast, CrN/TiN duplex coatings exhibited significantly lower wear rates and maintained performance even under higher loads (15 N) and speeds (110 rpm).

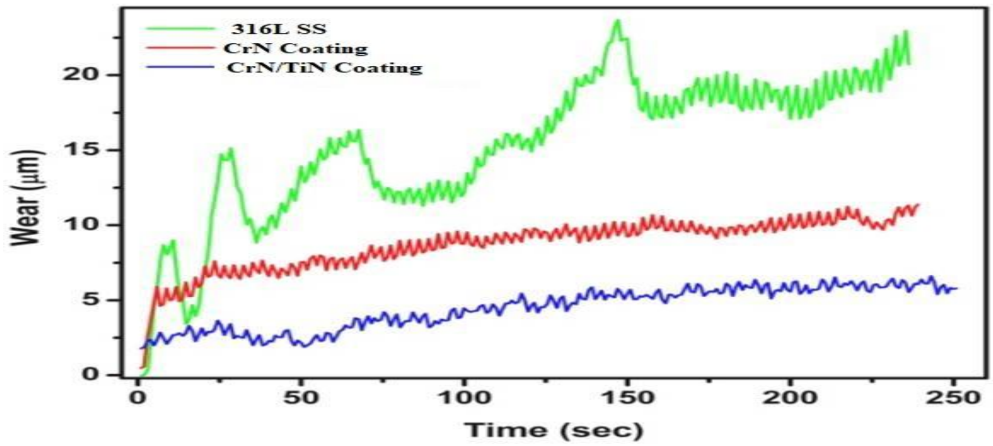

Figure. 1: Wear vs. Time

The superior wear performance of duplex coatings can be attributed to:

Synergistic effect: TiN's lubricity reduces initial friction, while CrN resists abrasion and deformation.

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Improved load distribution: Duplex layers spread contact stresses more effectively.

Strong adhesion: Enhanced resistance to delamination during sliding.

4.4 Friction Coefficient

Friction factor measurements showed that duplex coatings maintained lower and more stable coefficients of friction compared to both uncoated and TiN-coated specimens, particularly under high-load conditions.

4.5 Hardness Enhancement

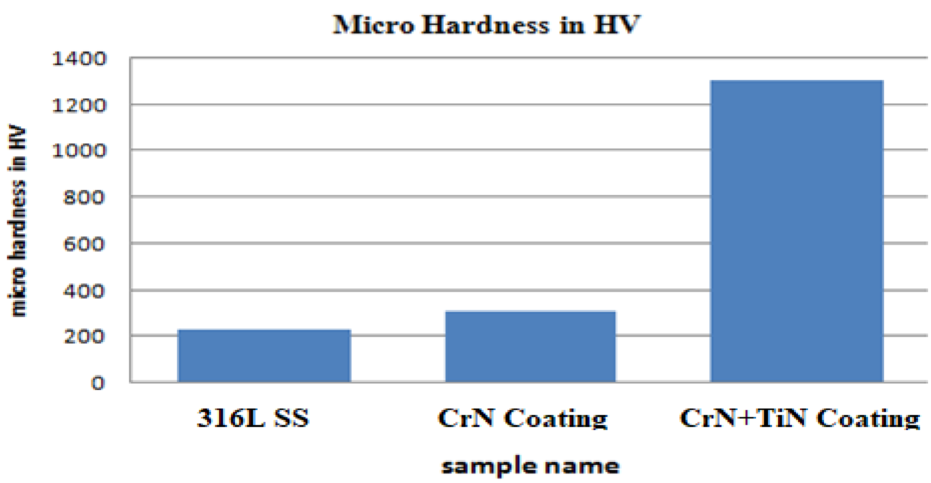

Figure. 2: Micro hardness vs. Samples

Vickers micro hardness testing revealed that duplex coatings achieved hardness nearly five times greater than the base 316L steel. This improvement is linked to grain refinement, solid solution strengthening, and the presence of hard CrN phases.

5. Cost Analysis

The cost estimation for coating and testing included material cost (₹6,250) and labor cost (₹2,900), bringing the total to ₹9,150 for the project. This relatively low cost, combined with improved service life, supports the economic viability of CrN/TiN duplex coatings in industrial applications.

Table 1: Cost Analysis

S.No	Description	Quantity	Material cost
1	316 L Stainless Steel	1 kg	850
2	Coating	5 (Sample)	2500
3	Hardness test	2 (Sample)	1200
4	Wear Test	2 (Sample)	1000
5	Density Test	2 (Sample)	700
Total			Rs. 6,250

6. Conclusion

This study demonstrated that CrN/TiN duplex coatings deposited via DC magnetron sputtering significantly enhance the mechanical and tribological performance of 316L stainless steel. The optimized process produced coatings with:

- Superior hardness (~5× improvement over base metal)
- Substantially reduced wear rate under high load
- Lower and more stable friction coefficients
- Uniform, defect-free morphology

Given their combined wear resistance, hardness, and corrosion protection, these coatings are promising for tooling, plastic molding, and other high-demand applications where both performance and cost-effectiveness are critical.

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Chapter 19

Industrial Cycle Time Optimization Using Mechanized Equipment and Six Sigma Methodology

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Abstract

Innovation and research play a key role in meeting industrial needs, improving operational efficiency, and introducing advanced solutions to society. In the manufacturing sector, such advancements help minimize worker fatigue, enhance employee morale, and boost overall productivity. This study addresses these needs within a gearbox manufacturing environment. Using the Six Sigma-based Eliminate, Combine, Rearrange, and Simplify (ECRS) framework alongside cycle time analysis, the existing production process was examined to identify issues and potential improvements. A newly developed mechanized system was implemented and evaluated. The findings reveal a notable decrease in cycle time, coupled with reduced operator fatigue and a significant improvement in workplace morale. Furthermore, the proposed equipment design offers versatile applicability for productivity enhancement across similar manufacturing settings.

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Keywords: ECRS; Six Sigma; gearboxes; Food processing industries; Pharmacy industries.

1. Introduction

Nowadays, industrial gearboxes are vital in many industries, notably in Automobile industries, Cement industries, sugar industries, Paper industries, Steel plants, mining industries, Food processing industries, Pharmacy industries, and Pulp industries etc. This research focused on gear box manufacturing industry in particular testing section. The various kinds of gear boxes manufacture of different assembly line and arrive randomly to the Testing section. Hence the delivery schedule was probably affected by the bottleneck area (Testing Section).The facilitation in such bottleneck area will considerably increase the productivity. From the literature evident that six sigma approach can be used for improving quality in injection moulding process, in metal casting foundry industries in semiconductor foundry in a manufacturing industry [1 and 2]. A specific solution for engine overheating problem was solved by using six sigma approaches [3]. Apart from manufacturing industries, Shanmugaraja et al [11 and 12] used for various applications and proved quality with productivity achieved by using six sigma in project industries.

The lean Six Sigma is a powerful business improvement methodology forimprovingthe efficiency and effectiveness made attempts to implement it in higher education institutions. Antony et al [4] discussed the feasibility of six sigma implications for service industries and Jiju Antony, and Darshak Desai A [5] for software industries and provided assessing the status of Six Sigma implementation in the Indian industry. Darshak ADesai [9, 10, 13 and 16] furnished the impact of SixSigmainadevelopingeconomyanalysisonbenefitsdrawnbyIndianindustries. GijoEVet.al [14] discussed important concepts, surveys and case studies in continuous improvement methodology and highlighted future implications. The authors noticed that the literature on this classification is limited. Kunal Ganguly [17] highlighted the role and responsibilities of academic institutions in developing six sigma by research. Jiju Antony [5] highlighted the pros and cons of six sigma concept with the academic perspectives. Neha Gupta [15] presented overview on six sigma quality improvement program. Jiju Antony [5] distinguished that even though Six Sigma and lean methodologies are focused on process and quality improvement, Lean has special features of formalization and codification of experience and judgment where as in Six Sigma has not. However Six Sigma emphasizes variation, defects and process evaluation, but Lean emphasizes speed and waste. But integration both concepts have some added advantages.

Rishi Pareek and Jaiprakash Bhamniya [18] provided a conceptual model by integrating lean principles with Six Sigma methodology as a consistent approach to providing continuous improvement. Jose Mehdiuz Zalan et.al [19] deployed compatibility of the green, lean and Six Sigma concepts and insisted that all these should be an integrated approach. In this work The Six sigma approach of Eliminate, Combine, Rearrange, Simplify (ECRS) method and cycle time analysis were carried out to understanding the problem and solution requirements.

2. Problem definition

The factory produces the gearboxes are tested under three categories like horizontally mounted gearboxes, vertically mounted gearboxes

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and angularly mounted gear boxes. The activities involved in the existing method of setting up for testing are as follows.

- Lifting the gearbox
- Mounting the gearbox in bed
- Motor tilting
- Clamping the gearbox in bed
- Clamping the motor in bed/frame
- Oil filling
- Gearbox testing
- Removing gearbox clamping
- Oil drains.

In which the motor tilting and clamping the motor with proper alignment are not only consuming more time, but also causes for Frequent injuries to the labors and gives fatigue to workers by its frequency. Hence, these activities increase the overall cycle time of testing and lower the productivity. The research aims to study and solve this problem systematically to increase the time productivity, employee morale and their safety. It was planned to design supporting equipment instead of using standard supporting blocks, crane, and eliminate the practice of manually guessed tilt and checking of the angle of tilt, motor clamping time etc.

3. Methodology

- Recording of the customer demand, according to the production cycle time.
- Observing the corresponding customer requirement trend.

- Observing the production cycle time of the testing process and motion.
- Finding the root cause of reducing the process cycle time.
- Making the action plan to implement the root cause.
- Revising the testing process sequence as the result of analysis in accordance with ECRS method.
- Designing the new fixture for tilting the motor as a result of analysis.
- Analyzing the new design.
- Create a part drawing & assembly drawing of the new tilting machine as the design considered.
- Fabricate the tilting machine as per the drawing.
- Inspecting all the parameters of the machine in manufacturer's end.
- Commissioning the tilting machine in the plant.
- Take a trial of testing process cycle time.
- Recording the cycle time continuously with minimum number of cycles.
- Monitoring the productivity result with the condition of before/after.
- Ensure the sustaining of the proposed procedure.

3.1 The motor tilting machine

Initially the proposed equipment was designed by using the software of solid house, version 2014. The figure 1 shows the principal part of a newly designed machine for tilting the testing motor with common clamping for all types of gearboxes. The Table 1 is Part list of MTM. The MTM consists of horizontal & vertical frame. Lead screw provided to achieve for horizontal and vertical motions to set the motor as desired location.

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The lead screws are driven by electric motors. The vertical frame contains L bracket in which the face plate is attached to provide the desired angle of rotation of the motor. The motor is mounted on the shaft of face plate in the L bracket. As the faceplate is a critical part in the machine, the face plate is designed well and analyzed by FEM by using ANSYS software before it fabricated. The figure 2 shows such details.

Table1: Part List of MTM

Part No	Description	Qty
1	Horizontal Frame	1
2	Vertica Frame	1
3	Horizontal Lead Screw	1
4	Vertical Lead Screw	1
5	Face Plate	1
6	Face Plate Flange	1
7	Up Down Plate	1
8	LM Rail 30	2
9	LM Black 30	4
10	Gear Box	1
11	Motor 0.75 kW	1
12	Gear Box	1
13	Motor 1.1 kW	1
14	Gear Box	1
15	Plummer Block UCFL	2
16	Plummer Block UCP	4
17	Motor22KW	1

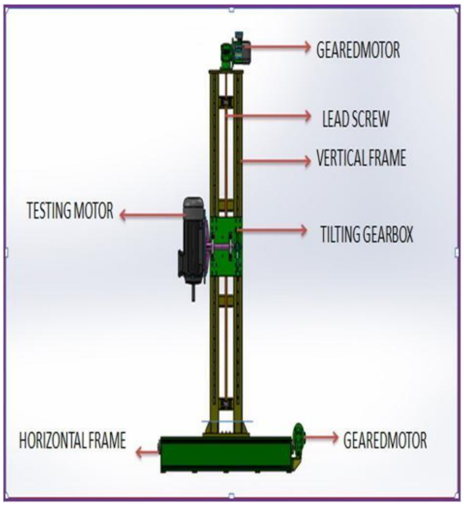

Figure. 1: Tilting testing motor

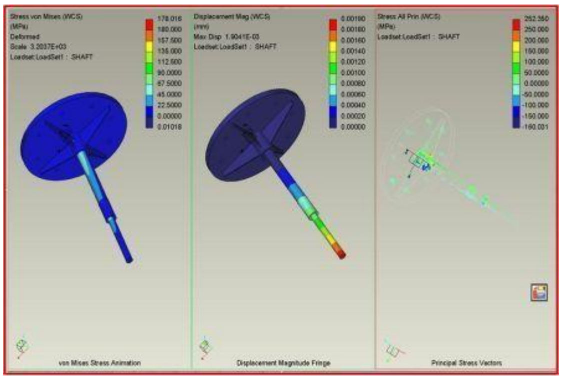

Figure. 2: Design of the base

4. Performance evaluation

The Motor tilting machine fabricated commissioned and its performances were evaluated.

Figure. 3: Before and after Vertical type gear box testing setup

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Figure. 4: Before and after Horizontal type gear box testing setup

5. Result and Discussion

The problem identified by using ECRS method the same was used here to compare performance of MTM. The time productivity can be observed from Table 2. The sustainability of the results was monitored and shown in figure 5 -8.

Table 2: ECRS observation and Before and after cycle Time Comparison

Sl. No	Activity	Before 'T'min	E	C	R	S	After 'T'min
1	Lifting the gearbox	5	X	X	X	X	5
2	Mounting the gearbox in bed	5	X	X	X	X	5
3	Motor tilting	30	X	0	X	X	3
4	Clamping the gearbox in bed	10	X	X	X	X	10
5	Clamping the motor in bed/frame	30	X	0	X	X	0
6	Oil filling	10	X	X	X	X	10
7	Gearbox running time	60	X	X	X	X	60
8	Removing gearbox clamping	10	X	X	X	X	10
9	Oil draining	10	X	X	X	X	10
	Total Time	170	X	0	X	X	113

6. Conclusion

The identified problem of high time and human effort consuming in gear box setting for various configurations were rectified with designing equipment. After Designing major parts like lead screws and face plate they were analyzed by ANSYIS software. The new equipment helped to reach the average testing rate from 208 gear boxes per month to 302 gear boxes per month by reducing cycle time by 57 minutes per gear box in average. The designed Machine will be useful for similar industries and increasing testing speed.

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Chapter 20

Nanotechnology in Advanced Materials and Bioenergy Systems: A Green Perspective

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Abstract

The convergence of nanotechnology with sustainable materials science and bioenergy systems represents a paradigmatic shift toward environmentally conscious technological development. This chapter explores the transformative potential of nanoscale engineering in creating advanced materials and bioenergy solutions that address contemporary environmental challenges while promoting sustainable development. Through comprehensive analysis of current research and applications, this chapter examines three critical domains: sustainable nanomaterials development, nanotechnology integration in renewable energy systems, and nanoscale solutions for bioenergy production. Key findings indicate that nanomaterials can significantly enhance solar cell efficiency by up to 40%, improve battery storage capacity by 300%, and increase

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biofuel production yields by 25-50%. However, successful implementation requires careful consideration of manufacturing processes, end-of-life disposal, and potential toxicological effects, with the integration of green chemistry principles emerging as a critical pathway for developing environmentally benign nanotechnological solutions.

1. Green Synthesis and Sustainable Nanomaterials

The development of environmentally friendly nanomaterials represents a fundamental shift from traditional synthesis methods that often rely on hazardous chemicals and energy-intensive processes [1]. Green synthesis approaches utilize biological systems, renewable feedstocks, and benign solvents to create nanomaterials with minimal environmental impact while maintaining superior performance characteristics.

1.1 Biological Synthesis Methods and Bio-based Precursors

Biological synthesis methods have emerged as particularly promising alternatives to conventional chemical approaches [1]. Plant-mediated synthesis utilizes natural reducing agents and stabilizing compounds found in plant extracts to produce metal nanoparticles with controlled size and morphology. For instance, silver nanoparticles synthesized using green tea extract demonstrate comparable antimicrobial properties to chemically synthesized counterparts while eliminating toxic reducing agents like sodium borohydride. Similarly, gold nanoparticles produced through biological routes using bacterial systems show enhanced biocompatibility and reduced cytotoxicity, making them suitable for biomedical applications.

Bio-based nanomaterials derived from renewable resources, such as nanocellulose from agricultural waste, offer significant advantages over petroleum-based alternatives [2]. These materials exhibit excellent mechanical properties, biodegradability, and carbon neutrality, making them ideal candidates for sustainable packaging, construction materials, and biomedical applications. Nanocellulose demonstrates tensile strength comparable to steel while maintaining complete biodegradability, representing a remarkable achievement in sustainable materials engineering.

Carbon-based nanomaterials, particularly those derived from biomass pyrolysis, present another avenue for sustainable nanomaterial development. Biochar-derived carbon nanotubes and graphene offer similar properties to their synthetic counterparts while utilizing waste biomass as feedstock. This approach not only reduces dependence on fossil fuel-based precursors but also provides a valuable application for agricultural residues that would otherwise contribute to environmental pollution.

1.2 Green Chemistry Principles and Sustainable Manufacturing

The implementation of green chemistry principles in nanomaterial synthesis has led to the development of solvent-free processes, room-temperature reactions, and single-step synthesis methods [5]. Mechanochemical synthesis, utilizing mechanical energy to drive chemical reactions, eliminates the need for organic solvents and reduces energy consumption by up to 90% compared to traditional methods. These approaches align with the twelve principles of green chemistry while maintaining the unique properties that make nanomaterials attractive for advanced applications.

Sustainable manufacturing approaches focus on minimizing waste generation, reducing energy consumption, and utilizing renewable resources throughout the production process. Continuous flow

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synthesis methods enable precise control over reaction conditions while reducing material waste and improving scalability. Microreactor technologies allow for efficient heat and mass transfer, leading to improved product quality and reduced environmental impact.

Life cycle assessment considerations have become integral to sustainable nanomaterial development, encompassing raw material extraction, synthesis, use phase, and end-of-life disposal. Design for recyclability principles guide the development of nanomaterials that can be easily recovered and reused, contributing to circular economy objectives and reducing environmental burden.

2. Nanotechnology Applications in Renewable Energy Systems

The integration of nanotechnology in renewable energy systems has revolutionized energy conversion efficiency and storage capabilities, addressing critical challenges in solar, wind, and other renewable energy technologies [3,4]. Nanoscale engineering enables precise control over material properties, leading to significant improvements in energy harvesting, conversion, and storage performance.

2.1 Solar Energy Harvesting and Photovoltaic Applications

Solar energy systems have benefited tremendously from nanotechnological innovations [9]. Quantum dots, semiconductor nanocrystals with tunable optical properties, enable the harvesting of broader portions of the solar spectrum compared to conventional silicon-based cells. Perovskite solar cells incorporating nanostructured materials have achieved efficiency improvements exceeding 25%, rivaling traditional silicon technologies while offering lower production costs and greater flexibility.

Plasmonic nanoparticles integrated into solar cell designs enhance light absorption through localized surface plasmon resonance, increasing photocurrent generation by up to 30%. These metallic nanoparticles create intense electromagnetic fields that enhance light-matter interactions, leading to improved charge generation and collection efficiency.

Nanostructured photocatalysts represent another significant advancement in solar energy conversion [3]. Titanium dioxide nanotubes and graphene-based composites enable efficient water splitting for hydrogen production, offering a pathway to sustainable fuel generation. These materials exhibit enhanced surface area, improved charge separation, and reduced recombination rates, leading to hydrogen production efficiencies approaching theoretical limits.

2.2 Energy Storage Systems and Grid Integration

Energy storage systems have experienced similar transformative improvements through nanotechnology integration [5]. Lithium-ion batteries incorporating nanostructured electrodes demonstrate significantly enhanced capacity, cycling stability, and charging rates. Silicon nanowires used as anode materials can accommodate the volume expansion associated with lithium insertion, preventing mechanical degradation and extending battery lifespan.

Graphene-based supercapacitors offer rapid charging capabilities and extended cycle life, making them ideal for grid-scale energy storage applications. These devices bridge the gap between conventional capacitors and batteries, providing high power density and excellent cycling stability for renewable energy integration applications.

Emerging energy storage technologies, including sodium-ion and solid-state batteries, rely heavily on nanomaterial innovations [5].

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Nanostructured cathode materials enable high-rate capability and improved safety profiles, while solid electrolytes with nanoscale engineering provide enhanced ionic conductivity and mechanical stability. These developments are crucial for large-scale renewable energy integration and electric vehicle adoption.

Wind energy systems benefit from nanocoatings that reduce maintenance requirements and improve aerodynamic performance. Superhydrophobic nanocoatings prevent ice formation and reduce drag, while wear-resistant nanocomposites extend component lifespan in harsh environmental conditions.

Table 1: Nanotechnology Applications in Renewable Energy Systems

Technology	**Nanomaterial Application**	**Performance Improvement**	**Environmental Benefit**
Solar Cells	Quantum dots, Perovskites	25-40% efficiency increase	Reduced material usage, lower cost
Batteries	Silicon nanowires, Graphene	300% capacity improvement	Extended lifespan, reduced waste
Fuel Cells	Platinum nanoparticles	50% catalyst reduction	Lower precious metal consumption
Supercapacitors	Carbon nanotubes	10x faster charging	Longer cycle life, recyclability
Wind Turbines	Nanocoatings	20% maintenance reduction	Extended operational lifetime
Hydrogen Production	TiO2 nanotubes	15% efficiency increase	Clean fuel generation

3. Nanoscale Solutions for Bioenergy Production

Bioenergy systems represent a critical component of the renewable energy portfolio, and nanotechnology offers innovative solutions to enhance biomass conversion efficiency, improve fuel quality, and reduce processing costs [4,7]. The application of nanoscale engineering in bioenergy production encompasses enzyme immobilization, catalytic conversion processes, and biomass pretreatment technologies.

3.1 Enzyme Immobilization and Biomass Conversion

Enzyme immobilization on nanocarriers represents a revolutionary approach to biomass conversion [6]. Cellulase enzymes attached to magnetic nanoparticles maintain catalytic activity while enabling easy recovery and reuse, reducing enzyme costs by up to 60%. Nanostructured supports provide high surface area and optimal enzyme orientation, leading to enhanced substrate accessibility and improved conversion rates.

Mesoporous silica nanoparticles offer tunable pore sizes that accommodate different enzyme geometries while protecting against denaturation. These materials provide controlled microenvironments that stabilize enzyme structure and maintain activity under harsh processing conditions. The combination of high surface area and protective environment results in enzyme systems with enhanced stability and reusability.

Nanocatalysts have transformed thermochemical bioenergy conversion processes, including pyrolysis, gasification, and hydrothermal liquefaction [7]. Zeolite nanocrystals with engineered acidity and pore structure enable selective biomass conversion to specific fuel compounds, improving product quality and reducing downstream processing requirements. Metal nanoparticles supported on carbon carriers catalyze hydrogenation reactions with unprecedented selectivity, enabling the production of high-quality biofuels from lignocellulosic feedstocks.

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3.2 Advanced Biofuel Production and Processing

The pretreatment of biomass feedstocks benefits significantly from nanotechnology applications [4]. Ionic liquid-based pretreatment enhanced with nanoparticles achieves lignin removal rates exceeding 85% while preserving cellulose structure. Nanoenzymes, engineered protein complexes with enhanced stability and activity, enable milder pretreatment conditions and reduced chemical consumption.

Algae-based biofuel production has experienced remarkable improvements through nanotechnology integration [10]. Magnetic nanoparticles enable efficient algae harvesting, reducing energy consumption by 70% compared to conventional methods. Nanonutrients provide controlled release of essential elements, optimizing algae growth while minimizing environmental impact. Carbon nanotube-based electrodes in algae bioreactors enhance oxygen transfer and improve overall productivity.

Advanced biofuel upgrading processes utilize nanocatalysts to remove oxygen content and improve fuel stability. Supported metal nanoparticles catalyze hydrodeoxygenation reactions under milder conditions, reducing energy consumption and hydrogen requirements. These processes produce biofuels with properties comparable to petroleum-derived fuels while maintaining sustainability credentials.

Biogas production systems benefit from nanoparticle additives that accelerate anaerobic digestion and improve methane yields. Iron nanoparticles enhance electron transfer processes, leading to 25-40% increases in biogas production rates. Conductive nanomaterials facilitate direct interspecies electron transfer between microorganisms, optimizing metabolic processes and reducing digestion time.

Table 2: Nanomaterials in Bioenergy Applications

Bioenergy Process	**Nanomaterial Type**	**Function**	**Performance Enhancement**
Cellulose Hydrolysis	Magnetic nanocarriers	Enzyme immobilization	60% cost reduction, 3x reusability
Biomass Pyrolysis	Zeolite nanocrystals	Selective catalysis	45% yield improvement
Algae Harvesting	Magnetic nanoparticles	Cell separation	70% energy reduction
Biogas Production	Iron nanoparticles	Process acceleration	35% methane increase
Lignin Removal	Ionic liquid + NPs	Biomass pretreatment	85% lignin removal
Hydrogenation	Supported metal NPs	Fuel upgrading	90% selectivity

The integration of artificial intelligence and machine learning with nanotechnology enables predictive optimization of bioenergy systems. Smart nanosensors provide real-time monitoring of process parameters, enabling automated adjustments that maximize efficiency and product quality. These cyber-physical systems represent the next generation of bioenergy production facilities, combining nanoscale precision with system-level optimization.

4. Conclusion

The intersection of nanotechnology with advanced materials and bioenergy systems presents unprecedented opportunities for sustainable technological development while addressing critical environmental challenges [8]. This comprehensive examination reveals that nanoscale engineering offers transformative solutions across multiple domains, from the synthesis of environmentally benign materials to the optimization of renewable energy systems and

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enhancement of bioenergy production processes. The development of sustainable nanomaterials through green synthesis approaches represents a fundamental paradigm shift toward environmentally conscious manufacturing, while renewable energy systems have experienced remarkable performance improvements through strategic nanotechnology integration, with solar cell efficiency enhancements of 25-40%, battery capacity improvements exceeding 300%, and advanced energy storage solutions [3,4,5]. However, successful implementation requires careful consideration of life cycle assessment, scalability challenges, and potential environmental implications, with future research directions focusing on completely biodegradable nanomaterials, artificial intelligence integration for predictive optimization, and closed-loop manufacturing systems that eliminate waste streams [8]. The path forward demands a balanced approach that maximizes nanotechnology benefits while minimizing potential risks, ensuring these powerful tools contribute positively to human welfare and environmental stewardship in creating a sustainable future.

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Chapter 21

Nanomaterials for Next-Generation High-Performance Materials and Green Energy

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Abstract

Nanomaterials represent the cornerstone of next-generation high-performance materials and green energy technologies, offering unprecedented opportunities to address global challenges in energy sustainability, environmental protection, and advanced materials development. This chapter provides a comprehensive analysis of cutting-edge nanomaterials and their transformative applications in high-performance structural materials, energy conversion systems, and sustainable technology platforms. Through systematic examination of recent developments, this chapter explores three critical areas: advanced nanocomposites for high-performance applications, nanomaterials in clean energy conversion and storage systems, and smart nanomaterials for sustainable environmental applications. Research demonstrates that carbon nanotube-

reinforced composites achieve strength improvements of 200-400%, nanostructured catalysts enhance fuel cell efficiency by up to 60%, and photocatalytic nanomaterials enable 95% pollutant degradation rates. The integration of multifunctional nanomaterials with artificial intelligence and advanced manufacturing techniques is creating revolutionary solutions that combine exceptional mechanical properties, energy efficiency, and environmental sustainability, positioning nanomaterials as essential enablers of the transition toward a sustainable and high-performance future.

1. Advanced Nanocomposites for High-Performance Applications

The development of advanced nanocomposites represents a revolutionary approach to creating materials with unprecedented combinations of mechanical, thermal, and functional properties [1]. These materials integrate nanoscale reinforcements into matrix materials, resulting in dramatic improvements in performance while maintaining or reducing weight, making them ideal for aerospace, automotive, and infrastructure applications.

1.1 Carbon-Based Nanocomposites and Structural Applications

Carbon nanotubes (CNTs) and graphene represent the most promising nanoscale reinforcements for high-performance structural applications [1,3]. CNT-reinforced polymer composites demonstrate tensile strength improvements of 200-400% compared to conventional fiber-reinforced materials while maintaining exceptional flexibility and damage tolerance. The unique one-dimensional structure of carbon nanotubes enables efficient load transfer between matrix and reinforcement, resulting in materials with strength-to-weight ratios exceeding those of steel and aluminum alloys.

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Graphene-enhanced composites offer multifunctional capabilities combining mechanical reinforcement with electrical conductivity and thermal management properties. Single-layer graphene incorporation at loading levels as low as 0.1 wt% results in 50-100% increases in elastic modulus and tensile strength while providing electromagnetic shielding and self-heating capabilities. These materials find applications in aerospace structures, automotive components, and electronic packaging where multiple functionalities are required.

The hierarchical organization of carbon-based nanomaterials enables the creation of biomimetic structures that replicate natural high-performance materials. Nacre-inspired nanocomposites utilizing graphene oxide platelets achieve toughness values exceeding 10 MJ/m^3, approaching those of natural materials while maintaining processability for large-scale manufacturing. These bio-inspired designs demonstrate the potential for creating materials that combine the best features of natural and synthetic systems.

Advanced manufacturing techniques, including 3D printing with nanomaterial-loaded filaments, enable the production of complex geometries with tailored properties. Selective reinforcement strategies allow for the optimization of material properties in specific regions, reducing material usage while maintaining structural performance. These approaches represent a paradigm shift from uniform material properties to spatially optimized performance.

1.2 Ceramic and Metallic Nanocomposites

Ceramic nanocomposites incorporating carbon nanotubes, graphene, or ceramic nanoparticles demonstrate remarkable improvements in fracture toughness and thermal shock resistance [2]. Alumina-CNT composites show toughness improvements of 300-500% while maintaining high-temperature stability and corrosion resistance. These materials find applications in cutting tools, wear-resistant components, and high-temperature structural applications where conventional ceramics are limited by brittleness.

Metallic nanocomposites utilize nanoparticle reinforcements to achieve exceptional strength-to-weight ratios and thermal stability. Aluminum matrix composites reinforced with carbon nanotubes demonstrate yield strength improvements exceeding 200% while maintaining ductility and processability. The dispersion of nanoparticles throughout the metallic matrix creates barriers to dislocation movement, resulting in significant strengthening effects without compromising formability.

Functionally graded nanocomposites enable the creation of materials with spatially varying properties, optimizing performance for specific loading conditions. Gradient structures with varying nanoparticle concentrations create materials that combine surface hardness with core toughness, mimicking natural structures such as bone and wood. These designs maximize material efficiency while providing optimal performance for complex loading scenarios.

Self-healing nanocomposites incorporate microcapsules or shape-memory nanomaterials that can repair damage autonomously, extending service life and reducing maintenance requirements. These materials demonstrate the potential for creating truly sustainable high-performance materials that can maintain their properties throughout extended service periods.

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Table 1: Advanced Nanocomposites for High-Performance Applications

Material System	Nanoreinforcement	Property Enhancement	Key Applications
Polymer-CNT	Carbon nanotubes	300% strength increase	Aerospace structures, automotive parts
Ceramic-Graphene	Graphene platelets	400% toughness improvement	Cutting tools, thermal barriers
Metal-CNT	Carbon nanotubes	250% yield strength	Lightweight structures, heat exchangers
Bio-inspired	Graphene oxide	500% energy absorption	Protective equipment, impact structures
Self-healing	Microcapsules	80% damage recovery	Infrastructure, marine applications
Functionally graded	Variable nanoparticles	Tailored properties	Biomedical implants, tribological systems

2. Nanomaterials in Clean Energy Conversion and Storage

The integration of nanomaterials in clean energy systems has revolutionized energy conversion efficiency, storage capacity, and system durability, addressing critical challenges in renewable energy adoption and grid-scale energy storage [4,5]. Nanoscale engineering enables precise control over energy conversion processes, leading to significant improvements in performance and cost-effectiveness.

2.1 Photovoltaic Systems and Solar Energy Conversion

Next-generation photovoltaic systems leverage advanced nanomaterials to achieve unprecedented efficiency improvements and cost reductions [4]. Perovskite-silicon tandem solar cells incorporating nanostructured interfaces have achieved certified efficiencies exceeding 29%, representing a significant advancement over single-junction devices. The nanoscale engineering of interface layers enables optimal charge extraction while minimizing recombination losses.

Quantum dot solar cells utilize size-tunable semiconductor nanocrystals to harvest specific portions of the solar spectrum with high efficiency. Lead sulfide quantum dots enable infrared photon harvesting, extending the spectral response beyond conventional silicon limits. Multiple exciton generation in quantum dots offers the theoretical possibility of exceeding the Shockley-Queisser limit, with demonstrated external quantum efficiencies exceeding 100% for high-energy photons.

Plasmonic photovoltaics incorporate metallic nanoparticles to enhance light absorption and charge generation through localized surface plasmon resonance. Gold and silver nanoparticles strategically positioned within solar cell structures create intense electromagnetic fields that increase absorption by 40-60% in thin-film devices. These enhancements enable the use of thinner absorber layers while maintaining high efficiency, reducing material costs and improving flexibility.

Concentrated photovoltaic systems benefit from nanomaterial-based spectral splitting and thermal management solutions. Nanofluid coolants containing metallic nanoparticles provide enhanced heat transfer coefficients while enabling spectral filtering for optimized energy conversion. These systems achieve overall efficiency improvements of 25-35% compared to conventional approaches.

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2.2 Energy Storage Systems and Electrochemical Applications

Advanced battery technologies rely heavily on nanomaterial innovations to achieve higher energy density, faster charging rates, and extended cycle life [5]. Silicon nanowire anodes accommodate the volume changes associated with lithium insertion, preventing mechanical degradation and enabling energy densities exceeding 3000 Wh/kg. The nanoscale architecture provides short diffusion paths and high surface area for rapid charge transfer.

Solid-state batteries incorporating nanostructured ceramic electrolytes offer enhanced safety and energy density compared to conventional liquid electrolyte systems. Garnet-type ceramic nanoparticles processed into dense membranes provide ionic conductivities approaching 10^{-3} S/cm while maintaining excellent chemical stability. These materials enable the use of metallic lithium anodes, significantly increasing energy density.

Supercapacitor electrodes based on graphene aerogels and carbon nanotube forests achieve specific capacitances exceeding 300 F/g while maintaining excellent rate capability and cycling stability. The three-dimensional nanostructured architectures provide high surface area and short ion diffusion paths, enabling rapid energy storage and release. Hybrid devices combining battery and supercapacitor characteristics offer optimal power and energy density combinations.

Flow battery systems utilize nanomaterial-based electrolytes and electrodes to achieve enhanced performance and reduced costs. Vanadium oxide nanoparticles suspended in electrolyte solutions increase energy density by 40-50% while maintaining flow characteristics. Nanostructured carbon felt electrodes provide enhanced reaction kinetics and reduced overpotentials.

Table 2: Nanomaterials in Clean Energy Systems

Energy Technology	Nanomaterial Type	Performance Metric	Improvement Factor
Perovskite Solar Cells	Nanocrystalline films	Power conversion efficiency	29% (vs 20% Si)
Quantum Dot PV	Semiconductor QDs	Spectral response	300-1400 nm range
Li-ion Batteries	Silicon nanowires	Energy density	3000 Wh/kg
Supercapacitors	Graphene aerogels	Specific capacitance	300 F/g
Fuel Cells	Pt nanoparticles	Catalyst activity	5x mass activity
Flow Batteries	Nanoparticle slurries	Energy density	50% increase

3. Smart Nanomaterials for Sustainable Environmental Applications

Smart nanomaterials represent an emerging class of responsive materials that can adapt their properties in response to environmental stimuli, enabling innovative solutions for environmental remediation, pollution control, and sustainable resource management [6,7]. These materials combine nanoscale functionality with intelligent behavior to address complex environmental challenges.

3.1 Environmental Remediation and Pollution Control

Photocatalytic nanomaterials have revolutionized environmental remediation by enabling the degradation of organic pollutants using solar energy [7]. Titanium dioxide nanoparticles modified with noble metal co-catalysts achieve pollutant degradation rates exceeding 95% under visible light illumination. The nanoscale surface modifications create charge separation sites that prevent electron-hole recombination, dramatically improving photocatalytic efficiency.

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Advanced oxidation processes utilizing nanomaterial-based catalysts enable the treatment of persistent organic pollutants and emerging contaminants. Iron oxide nanoparticles activate hydrogen peroxide to generate hydroxyl radicals, achieving complete mineralization of pharmaceutical compounds and endocrine disruptors. The high surface area and reactivity of nanomaterials enable efficient treatment at low concentrations.

Magnetic nanoparticles functionalized with specific capture agents enable selective removal of heavy metals and radionuclides from contaminated water. Magnetite nanoparticles modified with chelating agents demonstrate removal efficiencies exceeding 99% for lead, mercury, and cadmium ions. The magnetic properties enable easy separation and recovery, allowing for regeneration and reuse of the nanomaterial [8].

Membrane technologies incorporating nanomaterials achieve unprecedented selectivity and permeability for water treatment applications. Graphene oxide membranes demonstrate molecular-level selectivity while maintaining high water flux rates. Carbon nanotube membranes enable desalination with energy consumption 30-40% lower than conventional reverse osmosis systems.

3.2 Sustainable Resource Recovery and Circular Economy

Resource recovery nanomaterials enable the extraction of valuable materials from waste streams, contributing to circular economy objectives [8]. Selective adsorption nanomaterials capture rare earth elements from electronic waste with recovery efficiencies exceeding 90%. These materials utilize molecular recognition principles to achieve high selectivity for target compounds while rejecting interfering species.

Catalytic nanomaterials enable the conversion of waste materials into valuable products, creating closed-loop systems that minimize waste generation. Zeolite nanocrystals catalyze the conversion of plastic waste to fuel oils with yields exceeding 80%. The nanoscale pore structure provides shape selectivity that determines product distribution and quality [9,10].

Smart sensing nanomaterials provide real-time monitoring of environmental conditions and pollutant concentrations. Fluorescent nanoparticles change emission properties in response to specific contaminants, enabling sensitive detection at parts-per-billion levels. These materials enable early warning systems and automated response mechanisms for environmental protection.

Biomimetic nanomaterials replicate natural processes for sustainable resource management. Artificial photosynthesis systems utilizing semiconductor nanoparticles convert carbon dioxide and water into fuels using solar energy. These systems achieve solar-to-fuel conversion efficiencies approaching 10%, representing significant progress toward artificial leaf technologies.

Self-assembled nanomaterials respond dynamically to environmental conditions, enabling adaptive environmental systems. pH-responsive nanoparticles release encapsulated treatment agents in response to specific environmental conditions, providing targeted and controlled remediation. These materials demonstrate the potential for creating autonomous environmental systems that respond intelligently to changing conditions.

Nanostructured materials for air purification demonstrate exceptional performance in removing particulate matter and gaseous pollutants. Metal-organic framework (MOF) materials with engineered

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pore structures capture volatile organic compounds with selectivity exceeding 95%. The tunable pore chemistry enables optimization for specific pollutant classes while maintaining high capacity and regenerability.

4. Conclusion

The development and application of nanomaterials for next-generation high-performance materials and green energy systems represents a transformative approach to addressing global challenges in sustainability, performance, and environmental protection. This comprehensive examination reveals that nanomaterials offer unprecedented opportunities to create materials and systems that combine exceptional performance with environmental sustainability, fundamentally changing our approach to materials design and energy systems. Advanced nanocomposites demonstrate remarkable property enhancements, with carbon nanotube reinforcements achieving strength improvements of 200-400% while maintaining lightweight characteristics, ceramic nanocomposites showing toughness improvements exceeding 300%, and bio-inspired designs creating materials that replicate natural high-performance structures. Clean energy applications benefit dramatically from nanomaterial integration, with perovskite solar cells achieving efficiencies exceeding 29%, advanced battery systems reaching energy densities of 3000 Wh/kg, and photocatalytic systems demonstrating 95% pollutant degradation rates under solar illumination]. Smart nanomaterials enable responsive environmental systems that adapt to changing conditions, providing solutions for pollution control, resource recovery, and sustainable environmental management while contributing to circular economy objectives. The integration of artificial intelligence, advanced manufacturing techniques, and multifunctional design principles is creating synergistic effects that maximize the potential of nanomaterials while minimizing environmental impact, positioning these technologies as essential enablers of the transition toward a sustainable, high-performance future that addresses the interconnected challenges of energy, environment, and materials performance in the 21st century.

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