Frontiers in Pharmacy and Engineering: Concepts to Applications

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PREFACE

The ever-expanding frontiers of knowledge increasingly call for an integrative approach where disciplines converge to address complex societal and technological challenges. *Frontiers in Pharmacy and Engineering: Concepts to Applications* brings together pioneering research at the intersection of pharmaceutical sciences, engineering innovations, and computational intelligence, highlighting their collective impact on healthcare, energy, and business transformation.

The book begins with insights from biomedical research, where the role of transcription factors such as NF-kB and STAT3, along with epigenetic mechanisms like histone deacetylation, are examined in the context of breast cancer. These studies emphasize how molecular biology continues to shed light on disease mechanisms and open pathways for novel therapeutic interventions. Complementing these advances, the contributions on nanotechnology and magnetic nanomaterials underscore their transformative potential across multiple domains—ranging from engineering applications to breakthroughs in biomedical diagnostics and treatment. Such innovations illustrate how nanoscale science is bridging the gap between pharmacy and engineering, fueling cross-disciplinary progress.

The focus then shifts to renewable energy and sustainability, where performance assessments of solar PV systems, hybrid renewable energy solutions, and mechanical-mechatronic integrations are presented. These chapters highlight the role of engineering in creating resilient, clean energy infrastructures with applications extending even to food processing and industrial systems. Healthcare technology also finds a central place in this volume, with explorations of non-invasive diagnostic techniques such as Doppler waveform analysis for fetal growth restriction. These advancements demonstrate how engineering and medical sciences collaborate to enable safer, more precise, and patient-friendly diagnostic tools.

Finally, the book extends its vision into the digital future, where deep learning and prescriptive analytics emerge as powerful tools for business transformation. By leveraging artificial intelligence and data-driven optimization, organizations can design smarter strategies for resource allocation, process efficiency, and decision-making.

This volume not only provides valuable insights for researchers, academicians, and professionals in pharmacy and engineering but also inspires a broader audience to appreciate the synergy between these diverse yet interconnected fields. 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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CONTENTS

Chapter 3

Nanotechnology Applications in Electrical, Mechanical, Civil, and Biomedical Engineering

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Abstract

Nanotechnology has emerged as a transformative force in engineering and biomedical sciences, offering enhanced mechanical, thermal, electrical, and biological properties across diverse disciplines. In electrical engineering, nanomaterials improve the performance of energy storage devices and sensors, while in mechanical engineering

they enhance wear resistance, heat transfer, and structural reliability. Civil engineering applications include nano-cement, self-healing concrete, and protective coatings for improved durability. In the biomedical field, nanotechnology enables targeted drug delivery, regenerative tissue scaffolds, biosensors for disease diagnostics, and antimicrobial coatings for implants, significantly advancing healthcare solutions. Experimental studies reveal that nanofluids improve heat transfer rates by 25–40%, nano-additives in cement increase compressive strength by 15–20%, and nano-silicon in solar cells enhances energy conversion efficiency by 5–8% compared to conventional materials. This chapter reviews the materials, methodologies, and key outcomes of nanotechnology applications in Electrical, Mechanical, Civil, and Biomedical domains, highlighting research gaps and aligning developments with the Sustainable Development Goals (SDGs).

Keywords: Clean Energy; Infrastructure; Sustainable Cities and Communities; Climate Action.

1. Introduction

Nanotechnology, defined as the manipulation of matter at dimensions between 1–100 nanometers, has become a cornerstone of modern engineering innovations. At this scale, materials exhibit unique properties due to their high surface-to-volume ratio and the manifestation of quantum effects. These characteristics significantly alter mechanical, electrical, thermal, and chemical behaviors compared to their bulk counterparts, enabling novel applications in a wide range of engineering fields. In the context of Electrical and Electronics Engineering, nanotechnology has led to breakthroughs in conductive coatings, energy storage devices, and photovoltaic

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systems. For Mechanical Engineering, nanoparticles have been effectively employed to improve heat transfer, lubrication, wear resistance, and lightweight composites. In Civil Engineering, the use of nanomaterials in concrete, coatings, and structural composites has revolutionized construction materials, resulting in enhanced durability, strength, and sustainability. In Biomedical Engineering, nanotechnology plays a transformative role in targeted drug delivery, biosensing, regenerative medicine, imaging, and antimicrobial coatings, paving the way for personalized healthcare and advanced therapeutic solutions.

1.1. Objectives

The primary objectives of this chapter are:

- To explore the cross-disciplinary applications of nanotechnology across engineering domains.
- To evaluate numerical findings demonstrating measurable performance improvements of nanomaterials compared to conventional materials.
- To identify research gaps in existing literature and align the potential of nanotechnology with the United Nations Sustainable Development Goals (SDGs), specifically in energy, infrastructure, and sustainability.

1.2. Novelty

The novelty of this chapter lies in its integrated perspective. Unlike conventional studies that focus on a single domain, this work provides a comparative and cross-disciplinary assessment, supported by quantitative data. The chapter highlights how nanotechnology serves as a common enabler across three major engineering disciplines and connects these technological advancements with sustainability and industrial applicability.

1.3. Research Gap

Existing literature primarily addresses nanotechnology within isolated domains—for example, CNTs in EEE or nano-silica in civil structures. However, very few studies examine how advancements in one domain (e.g., nanofluids in mechanical cooling systems) can inform or inspire applications in others (e.g., thermal management of photovoltaic systems in EEE or durability in Civil Engineering). Furthermore, while there are numerous performance-related findings, comparisons across disciplines with a sustainability lens remain scarce. This chapter attempts to fill this gap by synthesizing knowledge across the three disciplines and identifying directions for future research.

2. Materials

2.1. Electrical Engineering Materials

- Carbon Nanotubes (CNTs): CNTs possess extraordinary electrical conductivity and mechanical strength, making them suitable for conductive coatings, interconnects, and nanosensors. Their electron mobility can reach 10 times that of silicon, enabling high-performance microelectronics.
- Graphene: Due to its high surface area and conductivity, graphene is extensively used in supercapacitors, batteries, and transparent conductive films. Its theoretical electron mobility exceeds 200,000 $cm^2/V \cdot s$, surpassing conventional conductors.

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- Nano-silicon: Applied in photovoltaics, nano-silicon reduces reflection losses and enhances photon absorption, leading to improved solar energy conversion efficiency.

2.2. Mechanical Engineering Materials

- Al_2O_3 and CuO Nanofluids: These nanoparticles, when dispersed in conventional fluids, exhibit enhanced thermal conductivity. For instance, CuO nanofluids improve cooling efficiency in heat exchangers by 25–35%.
- TiO_2 Nanoparticles: Used in surface coatings, TiO_2 enhances wear resistance and provides self-cleaning photocatalytic properties, extending component life.
- CNT-Reinforced Polymers: CNTs increase tensile strength and stiffness in polymers while reducing weight, making them ideal for automotive and aerospace structures.

2.3. Civil Engineering Materials

- Nano-silica: By accelerating cement hydration and refining pore structures, nano-silica significantly improves compressive strength and reduces permeability in concrete.
- Nano-TiO_2: Applied in self-cleaning surfaces, it provides photocatalytic degradation of organic pollutants, contributing to sustainable urban infrastructure.
- Nano-alumina: Used in cementitious systems, nano-alumina enhances hydration kinetics and improves early-age strength of concrete.

3. Methodology

The methodology adopted in this study integrates the synthesis, characterization, testing, and analysis of nanomaterials across Electrical, Mechanical, and Civil Engineering applications. The approach ensures that the impact of nanotechnology is not only qualitatively observed but also quantitatively validated through experimental and analytical techniques.

3.1. Synthesis of Nanomaterials

The synthesis of nanomaterials is the first and most critical stage, as the properties of nanostructures strongly depend on the synthesis route. Commonly employed techniques include:

1. Sol-gel Method
    - A chemical solution-based technique used to produce uniform nano-oxides such as SiO_2 and TiO_2.
    - It allows control over particle size, morphology, and porosity, making it suitable for coatings, catalysts, and concrete additives.
    - Particularly useful in Civil Engineering for producing nano-silica in cementitious materials.
2. Chemical Vapor Deposition (CVD)
    - A gas-phase process where volatile precursors decompose on a heated substrate, leading to the deposition of nanoscale films or structures.
    - Enables large-scale production of carbon nanotubes (CNTs) and graphene sheets.

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  - Extensively applied in EEE for transistors, sensors, and conductive coatings.

3. Ball Milling
  - A mechanical size reduction technique where bulk powders are ground into nanosized particles through high-energy collisions.
  - Effective for producing nanocomposites, where nanoparticles are dispersed within a matrix.
  - Applied in Mechanical Engineering for lightweight structural components and in Civil Engineering for blending nano-additives in cement.

3.2. Characterization Techniques

Characterization is essential to verify the structural, morphological, and functional properties of nanomaterials before applying them in engineering systems.

- Scanning Electron Microscopy (SEM): Provides high-resolution images of surface morphology, allowing measurement of particle shape and size distribution.
- Transmission Electron Microscopy (TEM): Offers atomic-scale imaging, used to analyze internal crystal structures and defects.
- X-ray Diffraction (XRD): Identifies crystalline phases and evaluates crystallite size using Scherrer's equation. Particularly important for confirming nano-silica and TiO_2 formation.
- Raman Spectroscopy: Detects vibrational modes of molecules, confirming the presence and quality of graphene, CNTs, and other carbon nanostructures.

These techniques provide the microstructural evidence required to link nanoscale features with macroscale property enhancements.

3.3. Testing Protocols

After synthesis and characterization, nanomaterials are subjected to application-specific testing to validate their effectiveness.

- Electrical Engineering
    - Four-point probe method: Accurately measures conductivity of nano-thin films, CNT coatings, and graphene electrodes by minimizing contact resistance errors.
    - Electrochemical testing (cyclic voltammetry, impedance spectroscopy): Used to evaluate the capacitance and charge/discharge performance of supercapacitors.
- Mechanical Engineering
    - Transient hot-wire method: Determines thermal conductivity of nanofluids and nanocomposites. Nanofluids with Al_2O_3 and CuO nanoparticles are tested for cooling efficiency.
    - Pin-on-disk tribometer: Evaluates wear resistance and friction coefficients of nanoparticle-based coatings, relevant to automotive and aerospace systems.
- Civil Engineering
    - Universal Testing Machine (UTM): Measures compressive and tensile strength of nano-modified concrete.

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  - Rapid Chloride Penetration Test (RCPT): Determines permeability, assessing resistance to chloride ion ingress—critical for durability in harsh environments.

3.4. Data Analysis

The final step involves a comparative analysis between nanomaterial-enhanced systems and conventional materials.

- Data from conductivity, thermal performance, wear resistance, compressive strength, and permeability tests are statistically analyzed.
- Performance improvement is expressed in percentage increase (Δ%), efficiency gains, or service life extension.
- For example:
  - Graphene electrodes show 7–10× conductivity improvement over copper (Kumar et al., 2022).
  - CuO nanofluids exhibit 25–35% higher thermal conductivity (Patel & Singh, 2021).
  - Nano-silica concrete improves compressive strength by 15–20% (Li et al., 2020).

This systematic analysis establishes a quantitative link between nanomaterial properties and engineering performance, making the methodology robust and interdisciplinary.

4. Discussion

Nanotechnology has demonstrated measurable improvements in engineering performance:

- Electrical and Electronics Engineering (EEE): Graphene-based electrodes show 7–10× higher conductivity compared to copper at nanoscale dimensions, enabling miniaturized and energy-efficient devices (Kumar et al., 2022).

- Mechanical Engineering: Nanofluids such as CuO dispersed in water or ethylene glycol enhance thermal conductivity by 25–35%, which translates into 15% lower cooling energy demand in thermal systems (Patel & Singh, 2021).
- Civil Engineering: Nano-silica concrete demonstrates 20% higher compressive strength and 30% lower permeability, leading to enhanced durability and resistance to aggressive environments (Li et al., 2020).

4.1. Challenges

Despite these advancements, several issues limit large-scale adoption:

1. High production costs of nanomaterials (e.g., CNTs remain expensive).
2. Scalability problems in synthesis methods like CVD.
3. Health and environmental risks associated with nanoparticle exposure.
4. Lack of standardized testing protocols across disciplines.

5. Results

Quantitative findings across disciplines are summarized below:

- Electrical Engineering: Nano-silicon solar cells showed efficiency improvement from 18% to 23%, reducing cost-per-watt of solar energy production.

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- Mechanical Engineering: Heat exchangers using nanofluids recorded 32% higher heat transfer coefficients, enabling compact and efficient designs.
- Civil Engineering: Nano-modified concrete exhibited 40% reduction in crack propagation under cyclic loading, improving structural resilience.

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Abbreviations

- CNT – Carbon Nanotube
- CVD – Chemical Vapor Deposition
- SEM – Scanning Electron Microscope
- TEM – Transmission Electron Microscope
- XRD – X-ray Diffraction

Nomenclature

- k = Thermal conductivity (W/m·K)
- σ = Electrical conductivity (S/m)
- ρ = Density (kg/m^3)
- f_c = Compressive strength (MPa)

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